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TERA of Gas Turbine Propulsion Systems for RORO Ships

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Abstract: Recently, regulations on emissions produced by vessels from international maritime organizations, along with the instability of fuel prices, have encouraged researchers to explore fuels and technology that are cleaner than heavy fuel oil and diesel engines. In this study, we employed the TERA method to evaluate the feasibility of using gas turbine engines with cleaner fuels as a replacement for diesel engines as a propulsion system for RORO ships. A sensitivity evaluation and risk assessment were also conducted to investigate the impact of applied emission taxes on the economic results. The findings indicated that the diesel engine emitted higher nitrogen oxide emissions than the gas turbine fuelled by natural gas and hydrogen. The gas turbine with hydrogen had zero carbon dioxide emissions, making it a sustainable energy production option. The economic aspects were evaluated based on an international route, and they revealed that economic profitability significantly depended on fuel costs and consumption. The diesel engine fuelled by marine diesel oil and the gas turbine fuelled by natural gas were economically attractive, whereas the gas turbine fuelled by hydrogen was less viable due to its high operating cost. However, in a scenario where a carbon dioxide tax was introduced, the gas turbine fuelled by hydrogen showed high potential as a low-risk investment compared to the other technologies. In summary, this study demonstrated the usefulness of the TERA method in the maritime sector for selecting and comparing various propulsion systems.

Keywords: TERA; gas turbine; diesel engine; natural gas; hydrogen; emissions; nitrogen oxide; total carbon dioxide; net present value; payback period

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1. Introduction

One of the most common forms of international transportation is marine transport. The growth in marine transportation from 2007 to 2017 was approximately 25% [1]. Diesel engines power 90% of these vessels [2]. A side effect of the increase in marine transportation is that the vessels release harmful emissions such as sulfur oxide (SO_x), particulate matter (PM), and nitrogen oxide (NO_x), and emit approximately 2.2% of total carbon dioxide (CO_2) emissions [3]. Regarding the high emissions produced by diesel engines, the International Maritime Organization (IMO) established stringent regulations on air emissions and raised the possibility of applying a tax on CO_2 emissions to reduce harmful emissions from vessels [4]. The stringent regulations on harmful emissions have prompted researchers to explore marine fuel and technology alternatives that are cleaner than conventional ones [5]. To reduce polluting emissions, there are two possible solutions: using a different propulsion system or using cleaner fuels [6]. The most promising marine fuels are natural gas (NG) and hydrogen (HYD) [7,8]. NG fuel could reduce NOx and SO_X emissions by 85–100% and CO_2 emissions by approximately 20% compared to heavy fuel oil (HFO) [1]. NG fuel is expected to comprise approximately 32% of the shipping energy demand by 2050 [4]. HYD has zero carbon emissions and a high calorific value. By 2024, the HYD global market is expected to be 120 million tons [9]. The use of new technology is a promising approach that can be adopted in the marine sector, such as by using gas turbines instead of 4-stroke diesel engines [10]. 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 GT, which this paper aims to investigate. Previous studies on GT as a propulsion system for vessels are summarised in this section:

- Armellini [11] studied the performance of GTs fuelled with marine gas oil instead of diesel engines fuelled by HFO as the propulsion system for large cruise ships equipped with abatement devices such as scrubbers and selective catalytic reactor systems. The results of his study demonstrated that GTs are less efficient, much lighter, more compact, and can more easily reach low NO_x emissions than diesel engines.
- Barsi [12] studied the performance of GTs fuelled with LNG, analysed from an environmental point of view. The results of his study demonstrated that GT combustion technology, with steady-state and controlled flame temperature, grants a heavy reduction in NOx emission, easily matching nitrogen regulations for current marine engines.
- Kayadelen [13] studied the advantages of gas turbines and gas turbine systems in the marine industry. The results of his study demonstrated that the GT has advantages, especially in size, noise, vibration, and environmentally friendliness.
- Bonet [14] studied the performance of a liquified natural gas carrier powered by two marine gas turbines, several trip scenarios have been assessed for the liquefied natural gas carrier.
- Brynolf et al. [15] investigated the emissions impact of liquified natural gas (LNG), biomethanol, methanol, and liquified biogas. The results showed that the biofuels were a favourable solution for reducing emissions compared to HFO.
- Deniz and Zincir [16] examined HYD, LNG, ethanol, and methanol fuel based on many criteria. The results showed that HYD and LNG were the most suitable alternative fuels for the marine sector.
- Alzayedi [10,17,18] examined a combined cycle fuelled by LNG and marine diesel oil for a large container ship instead of a two-stroke diesel engine. Using numerical software and a TERA approach, the results indicated that LNG was a promising alternative fuel for the marine sector.
- Alkhaledi [19–22] evaluated a combined cycle for a liquefied hydrogen tanker fuelled by hydrogen using the TERA method. The results showed that the HYD fuel could achieve a zero-carbon footprint.

Techno economic environmental evaluation and risk evaluation is a method that utilises a mathematical model to simulate and evaluate the technical performance of an 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. Thus far, only a few studies have applied the TERA method to gas turbine propulsion systems for RORO ships instead of four-stroke diesel engines for international journeys. Hence, this study contributes:

- A comprehensive evaluation of the environment using an international journey mission to examine the emissions of NO_x and CO_2 from a GT fuelled with NG and HYD instead of a four-stroke diesel engine fuelled with MDO as a propulsion system for a RORO ship.
- An economical assessment, conducted through the net present value and payback period to evaluate the capital cost, operating cost, and maintenance cost of a GT propulsion system fuelled by HYD and NG. A four-stroke diesel engine fuelled by MDO was also evaluated for comparison.
- A risk analysis to examine the impact of an emission tax on the economic analysis.

The remainder of this paper is as follows. Section 2 describes the methods employed in this study. Section 3 defines the assumptions, simulation, results, and discussion. Section 4 presents the conclusion.

2. Methodology

The research methodology for this study consists of four distinct stages, which are displayed in Figure 1. In the first stage, in-house gas turbine performance software (Turbomatch) [23] was employed to evaluate a gas turbine model. The simulation was conducted using different fuels such as natural gas (NG), hydrogen (HYD), and marine diesel oil at various ambient temperatures. A diesel engine fuelled by marine diesel oil was used for comparison. The outputs of the gas turbine and diesel engine models, including the exhaust temperature, fuel flow, power, and efficiency were used as inputs for the second stage. The second stage involved the use of Poseidon simulator software to simulate ships with different propulsion systems and journey conditions. The third stage focused on an environmental model, which evaluated the NO_x and CO_2 emissions generated by the propulsion systems, taking into account the emission factors of the gas turbine and diesel engines. An economic model was also presented at this stage, which assessed the capital, maintenance, and operating costs of all propulsion systems using the net present value and payback period techniques. In the final stage, TERA evaluations were conducted on all propulsion systems under two different scenarios.

The primary aim of this study was to establish a comprehensive methodology to evaluate the TERA benefits of installing a GT instead of a diesel engine on a specialist RORO steel ship as the propulsion system. To achieve this goal, the study made several assumptions, which are listed below.

1. The voyages of the ship were expected to follow straight and direct routes.
2. The operational speed of the RORO steel ship was assumed to consistently be 14.5 knots.

2.1. GT Model

A gas turbine model was established using Cranfield in-house gas turbine performance software (Turbomatch) [23], which was capable of simulating various engine configurations for both design-point and off-design conditions. Specifically, the gas turbine used in the study was a GE LM500 simple cycle two-shaft marine gas turbine.

2.2. Diesel Engine Model

In this study, a diesel engine model was developed using MATLAB software installed on a reference vessel. The engine specifications were acquired from MAN B&W [24]. The primary focus of this model was to assess the performance of a diesel engine during a journey fuelled by MDO, which was used as the propulsion system of the ship. The model was considered to be the baseline scenario and was validated against the fuel consumption of the vessel.

The overall engine performance equations were as follows:

$$Indicated\ power = W_i * N * \left(\frac{n}{60 \times 2}\right) \tag{1}$$

where W_i is the net indicated work for one cylinder during one cycle (kJ), N is the number of cylinders, and n is the engine speed (rpm).

$$Brake\ power = W_b * N * \left(\frac{n}{60 \times 2}\right) \tag{2}$$

where W_b is the net indicated work for one cylinder during one cycle (kJ).

$$Brake\ thermal\ efficiency = W_b / Q_{in} \tag{3}$$

where Q_{in} is the input heat.

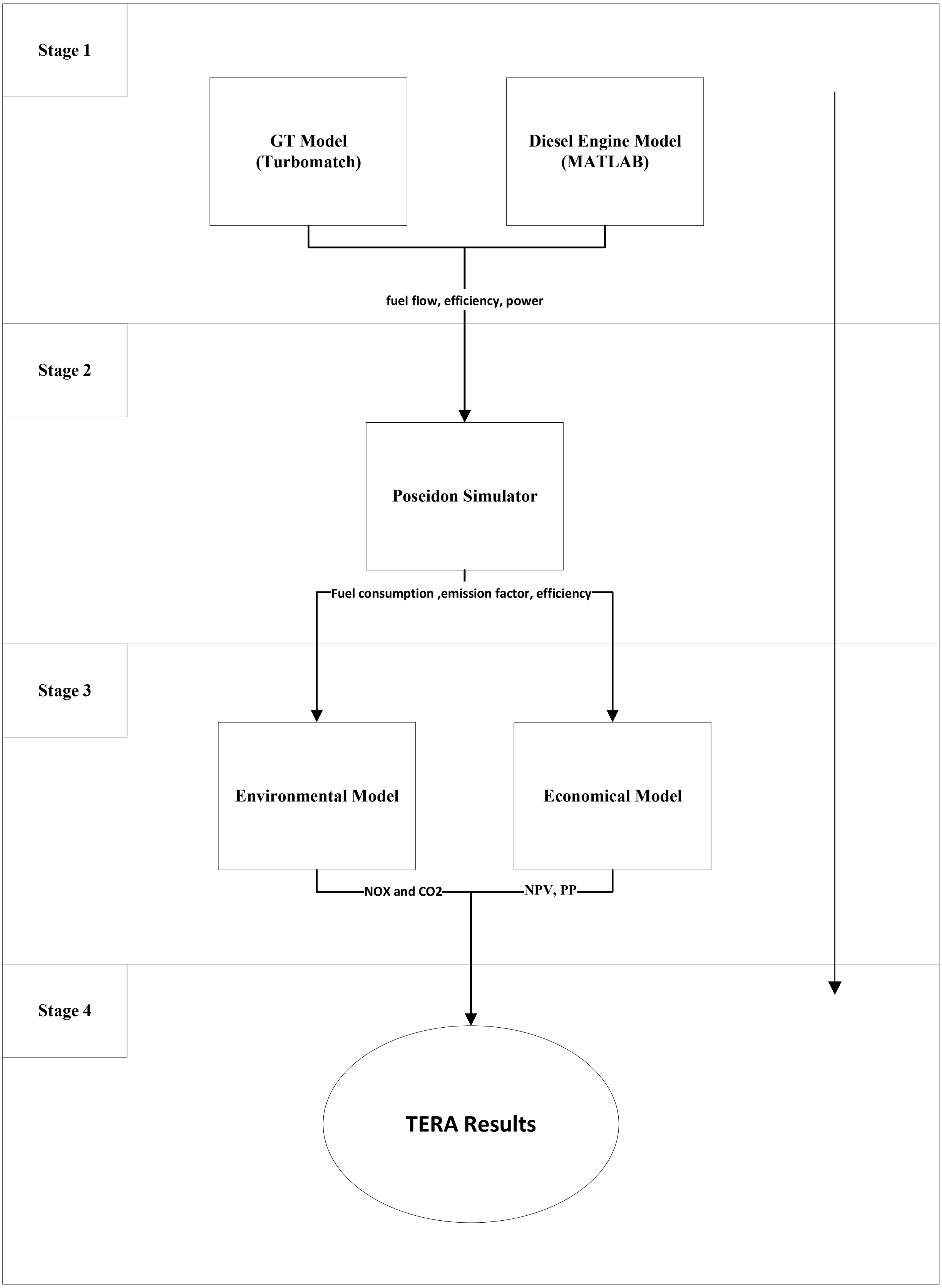

Figure 1. Methodology.

2.3. Poseidon Ship Simulator

The Poseidon ship simulator is thoroughly discussed in [24–27]. It consists of five subroutines that balance the power output of the propulsion machinery and the power needed to overcome the aerodynamic and hydrodynamic resistance of the vessel. The total resistance calculation enables the calculation of the required power of the propulsion system to maintain the velocity of the vessel. A resistance model is used to determine the propulsive power of the ship, using the method developed by Holtrop and Mennen [28]. The aerodynamic resistance of the ship, represented by wind resistance on its upper body, is modelled using the approach from [29]. However, the simulator does not account for the hydrodynamic resistance impacts from shallow water and propeller cavitation. Our study simulated container ships in open-sea conditions with different prime movers, including diesel engines and GT engines, during the journey. The journey was from the port of Shuwaikh, Kuwait, to the port of Mumbai, India, a distance of 1802 nautical miles as show in Figure 2. The weather for the journey was determined for three seasons—winter, summer, and mid-season—and over 24 h per day. The weather was selected based on the weather at the mid-point city, which was obtained from publicly available data [30]. The journey mid-point chosen for a more accurate weather prediction was Al Hadd, Oman.

Figure 2. The journey route.

2.4. Environmental Model

Emissions levels can be evaluated based on two distinct factors, namely engine power and fuel consumption [31]. For this research, the emissions were determined by taking into account the fuel consumption. The approach employed was as follows:

$$E = \sum \left(FC_{j,m} * EF_{I,j,m} \right) \tag{4}$$

where E represents the total emissions (kg/h), FC is the fuel consumption (tonnes/h), EF is the emissions factor (kg/tonnes), I is the emission type, j is the engine type (gas turbine, steam turbine, or 2-stroke diesel engine), and m is the type of fuel (NG or HYD).

To calculate the NO_x emission scale factor, the following equation was used [29]:

$$EF_{i,k} = \left(IF_{i,k} \times 10^{-6} \right) \left(\frac{P.V}{R.T} \times \frac{MW_k}{P_p} \right) \tag{5}$$

where $EF_{i,k}$ is the emissions factor (g/kWh), i is the engine type, k is the emission type, $IF_{i,k}$ is the concentration of gaseous species (ppm), P is the pressure (N/m^2), V is the engine exhaust flow rate (m^3/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).

The calculation of CO_2 emissions per kilogram of fuel was conducted using the following equation [32]:

$$kg\ CO_2 = \left(\frac{44}{12} \times C_m\right) \quad (6)$$

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

2.5. Economic Model

An objective of this research was to analyse the economic advantages of using a gas turbine compared with a traditional propulsion system in two different scenarios. The first scenario involved no CO_2 emissions tax, whereas the second scenario evaluated the impact of implementing a CO_2 emissions tax. The evaluation was conducted using the NPV and PP techniques to assess the performance of the different propulsion systems. The approach followed in this study was as follows:

- The capital cost included the cost of installing the propulsion system.
- The maintenance and operating costs took into account the fuel cost of the journey.
- A risk assessment was conducted to examine the impact of implementing the emissions tax on the economic analysis.

In the process of making investment decisions, the *NPV* is a crucial factor as it helps to predict future cash flows [33]. When selecting the *NPV*, there are two probable scenarios: it could be positive, surpassing the capital cost of the project; or it could be negative, resulting in a loss. The former is desirable, whilst the latter is not [34]. Therefore, the primary goal of this project was to reduce investor risk by using *NPV* calculations that indicated a good rate of return on the investment [35]. The *NPV* was calculated as follows [35]:

$$NPV = \sum_{t=0}^{n} \frac{x_t}{(1+R)^t} \quad (7)$$

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.

When a project is required to repay its initial investment, the payback period is an important factor to consider in capital budgeting. It is a useful tool to advise investors on the ability of a project to repay its initial investment. The calculation for the *PP* is as follows [36]:

$$PP = \frac{I_o}{C_o} \quad (8)$$

3. Results

3.1. Assumptions

This study presumed calm conditions for both the sea and air, which means that the wind resistance focused only on the resistance caused by the speed of the ship. For the research, a steel RORO ship was used. The primary characteristics were derived from publicly available information, as presented in Table 1. The reference point for the gas turbine (GT) simulation was based on the published data of currently used commercial gas turbines. These are outlined in Table 2.

Table 1. Main ship parameters.

Displacement (t)	11,012
Overall length (m)	126.3
Breadth (m)	20
Draught (m)	5.5
Speed (knots)	14.5

Table 2. Performance characteristics of the reference points for a gas turbine.

Parameter	Value
Thermal efficiency (%)	32
Exhaust gas temperature (K)	838
Exhaust mass flow (kg/s)	16.3
Power (kW)	4470
Pressure ratio	14.5
Specific fuel consumption (kg/kWh)	0.269

The two-stroke diesel engine model was inspired by MAN B&W. Its main parameters were derived from published data. These are listed in Table 3.

Table 3. Performance characteristics of the reference points for a diesel engine.

Parameter	Simulated Value
Exhaust gas temperature (°C)	546
Exhaust mass flow (kg/s)	9.11
Power (kW)	4500
Specific fuel consumption (g/kWh)	186.0
Stroke (mm)	400
Bore diameter (mm)	320

3.2. Route Analysis

The performance of a RORO ship between the selected ports was assessed over a period of one year (Table 4). Maximum ship use was assumed. The maximum capacity of the ship was taken into consideration during the assessment. This led to the assumption that it would require one day for maintenance, unloading, and loading during each journey. The ship was assumed to be operational for 330 days annually, as noted in [24]. The journey spanned three seasons—winter, summer, and mid-season—with 82.5 days each for winter and summer and 165 days for mid-season. To determine the number of journeys made per year and per season, it was assumed that the ship continuously operated on the specified route. These figures are presented in Table 4.

Table 4. Number of journeys per year and per season.

Journey	Trip Duration	Annual Trips	Annual Winter Trips	Annual Summer Trips	Annual Mid-Season Trips
Shuwaikh–Mumbai	5 d 04 h	61.1	15.2	15.2	30.5

The ambient temperatures determined for the journey during each season were the average temperature of each season from 2019 to 2022 is shown in Figure 3.

3.3. Environmental Results

The objective of the research was to examine the amount of CO_2 and NOx emissions produced using different fuels in gas turbines and diesel engines. The gas turbine was assumed to operate on natural gas and hydrogen, whereas the diesel engine was assumed to run on marine diesel oil. To estimate the emissions of CO_2 and NO_x from the diesel engine, we referred to publicly available data and determined that the range of emissions was between 560 and 620 g/kW·h and 8 and 10 g/kW·h, respectively [12,15–18]. The gas turbine chosen for the research used a low-NO_x combustor that produced low NO_x emissions, comparable with those of natural-gas-powered land-based gas turbines [36–40]. The NO_x concentrations of the natural gas and hydrogen fuels used in the research were obtained from [20,21]. The CO_2 emissions were determined by the fuel consumption and the carbon content of the fuel, which were both obtained from [40–42]; HYD fuel has zero CO_2 emissions [22,23]. Our findings on the NO_x and CO_2 emissions of each fuel are presented in Table 5.

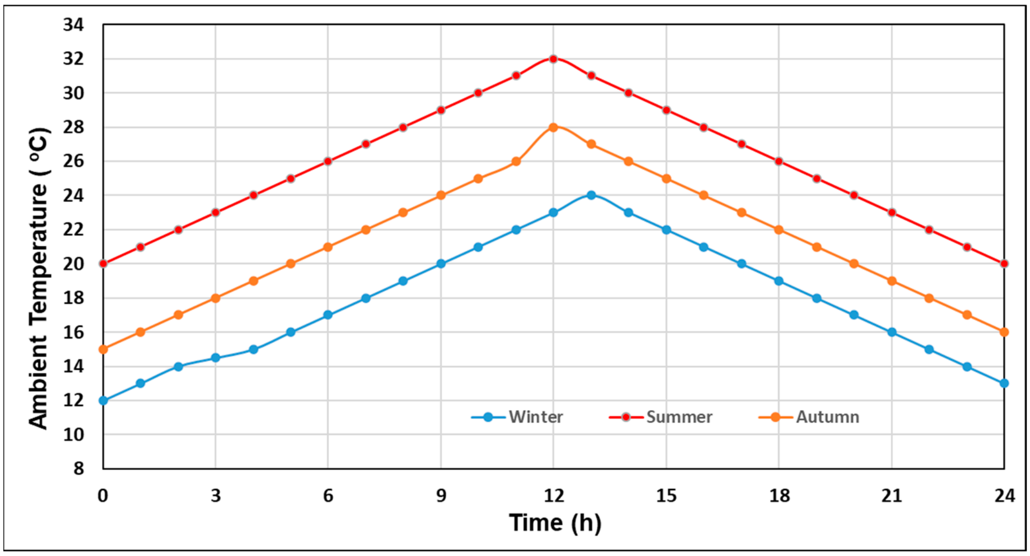

Figure 3. Ambient temperature of all seasons for the journey.

Table 5. NOx and CO_2 emissions of each fuel.

Emissions	Fuel Coefficient (kg CO_2/kg of Fuel)	NO_x (ppm)
NG	2.75	25
HYD	0	1.37
MDO	3.2	156

Figures 4 and 5 illustrate the CO_2 and NO_x emissions generated by the ship during its operation on the three-season routes. The NO_x emissions from the gas turbine were significantly lower than those from the diesel engine. The differences between the NO_x emissions from the gas turbine fuelled by natural gas and hydrogen, and the emissions from the diesel engine were approximately 84% and 89%, respectively. This was attributed to two main factors. The first factor was that the gas turbine burned a cleaner fuel than the diesel engine. The second and most significant factor was that the gas turbine operated at lower temperatures than the diesel engine. The gas turbine fuelled by natural gas had higher NO_x emissions than the gas turbine fuelled by hydrogen due to the lower concentration of NO_x in the hydrogen fuel. During the winter seasons, all propulsion systems have lower NO_x emissions due to an increase in mass flow, resulting in a higher power output and a lower exhaust temperature in cold weather.

The CO_2 emissions per hour during a single trip for different propulsion systems are shown in Figure 5. The diesel engine had higher efficiency; the gas turbine required a greater amount of fuel to meet the power demands of the vessel, resulting in higher CO_2 emissions than the diesel engine. The CO_2 emissions of the gas turbine fuelled by natural gas were approximately 14% higher than those of the diesel engine fuelled by marine diesel oil.

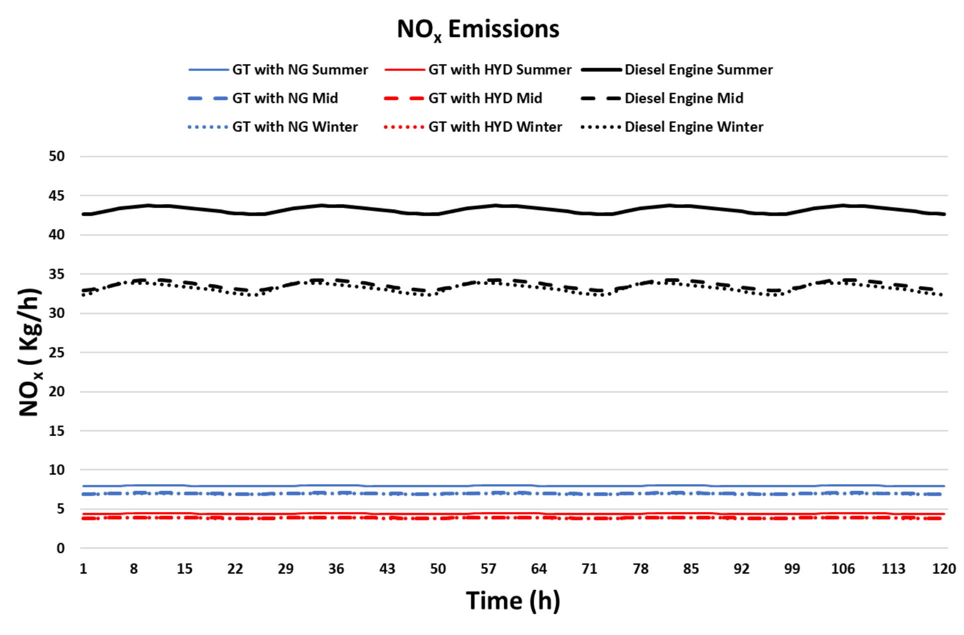

Figure 4. NO$_X$ emissions from propulsion systems of a ship travelling between Shuwaikh, Kuwait, and the port of Mumbai, India. GT: gas turbine; NG: natural gas; HYD: hydrogen; Mid: mid-season.

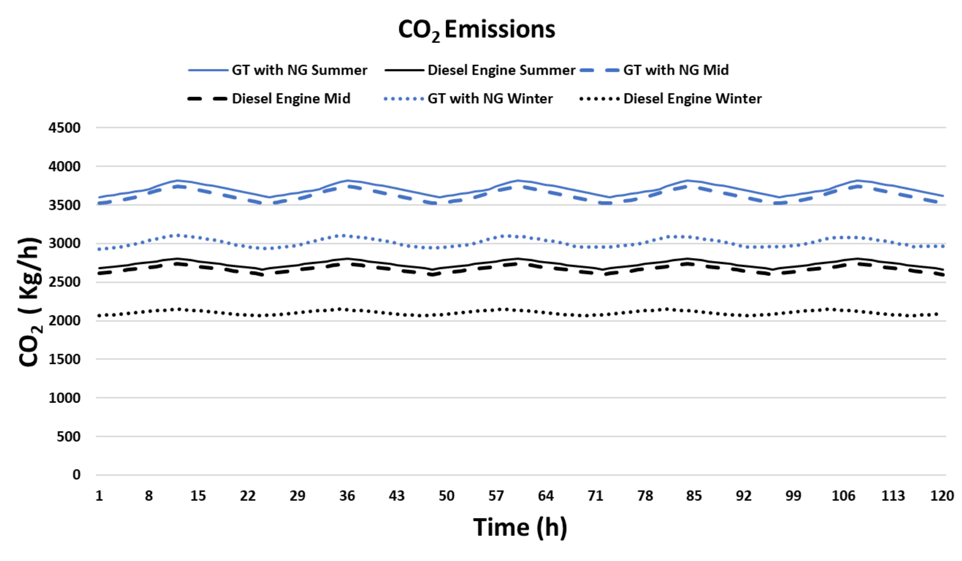

Figure 5. CO$_2$ emissions from propulsion systems of a ship travelling between Shuwaikh, Kuwait, and the port of Mumbai, India.

3.4. Economic Analysis

Capital and operating and maintenance (O&M) costs were estimated based on the scope and scale of the technology and the information available in the literature. The cost of a hull evaluation can be estimated via a number of methods, with prices of approximately 2.68–3.21 USD/kg [43–45]. The available literature suggests GT costs of 490 USD/kW and O&M costs of 4% of the capital costs per year, as well as installation costs of 30% of the capital costs [46–50]. For the diesel engine, the literature suggests a cost of 349 USD/kW, an operating and maintenance cost of 7% of the capital cost per year, and an installation cost of 30% of the capital cost [51,52]. The costs of the GT and diesel engines are shown in Table 6.

Table 6. Capital, maintenance, and installation costs of the analysed technologies.

GT (USD/kW)	490
GT O&M costs	4% of the capital cost per year
GT installation costs	30% of the capital cost
Diesel engine (USD/kW)	349
Diesel engine O&M costs	7% of the capital cost per year
Diesel engine installation costs	30% of the capital cost

To determine the fuel cost, a fuel price analysis was performed using an economic module. The NG prices for the European Union (EU) and Henry Hub markets [53] are shown in Figure 6.

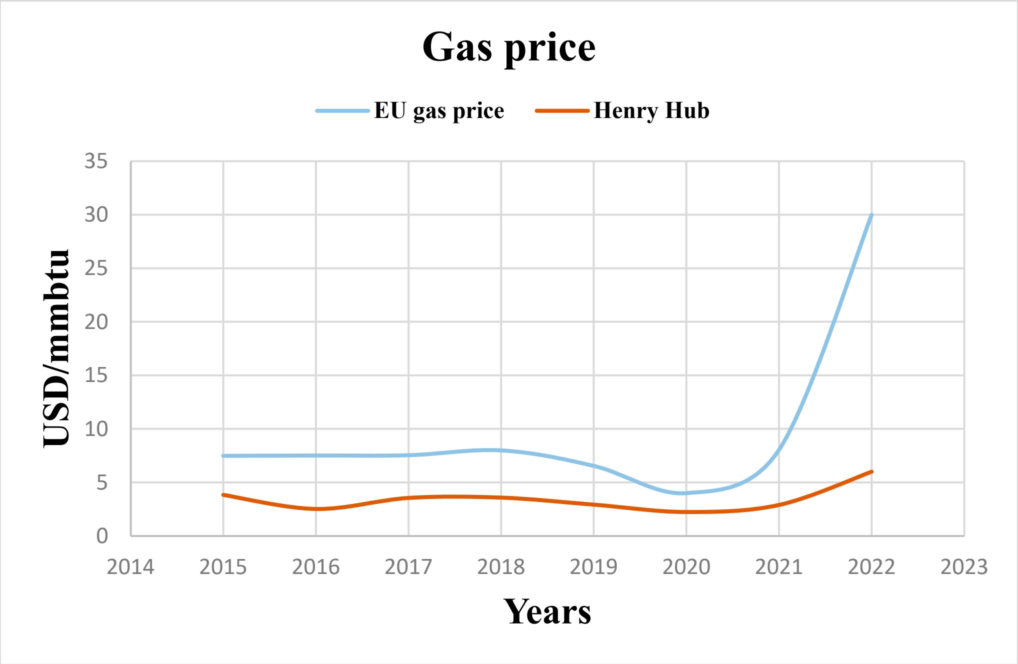

Figure 6. Natural gas fuel cost in European Union (EU) and Henry Hub markets.

To simplify the model, the NG price was assumed to be the average of the EU and Henry Hub market prices. The hydrogen price was assumed to be 2000 USD/tonne, obtained from [22]. As shown in Figure 7, the global price of MDO [54] in USD/tonne was considered in this study.

The prices of NG, HYD, and MDO that were used in this study are listed in Table 7.

Table 7. Fuel cost.

Fuel	**Price (USD/Tonne)**
NG	500
HYD	2000
MDO	900

Estimated revenue was calculated based on the number of voyages per year over 30 years, as the life cycle of a ship is 25–30 years [55]. The cash outflows were estimated on the basis of operating and maintenance costs as well as fuel costs. As a rough estimate, the shipping cost for a 20 ft container is USD 2114.26 [56,57].

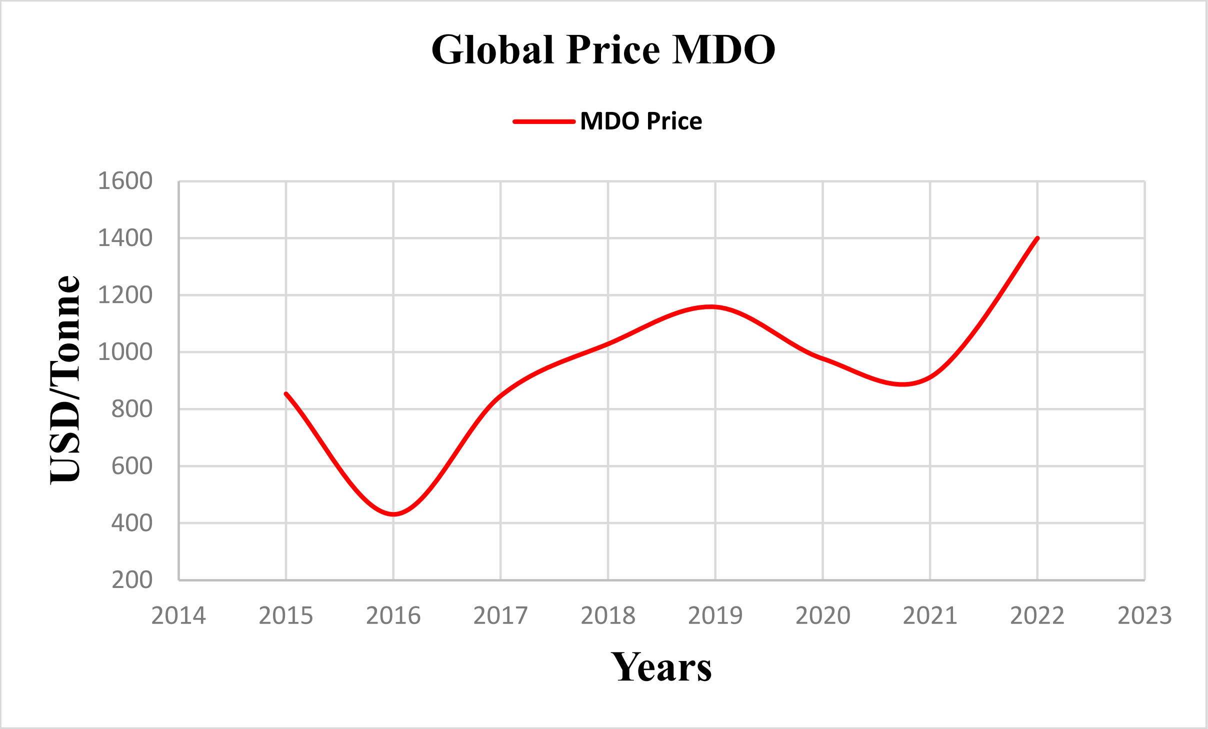

Figure 7. Global marine diesel oil fuel cost.

First Scenario:

A discount rate of 10% [21] was assumed in this study. Table 8 shows the NPV and PP of all the propulsion systems.

Table 8. Economic results for first scenario.

	GT NG	GT HYD	Diesel Engine
NPV	USD 12,191,843.3	USD 2,508,272.2	USD 13,926,599.1
PP	4.49 years	7.6 years	4.08 years

In the first scenario, the results of the GT fuelled by NG and HYD were less in terms of NPV than the diesel engine fuelled by MDO. This may have been due to the lower capital cost and fuel consumption of the diesel engine. The NPV of the GT fuelled by NG was lower than that of the diesel engine fuelled by MDO by approximately 12.45%. The GT fuelled by HYD had the lowest NPV due to the higher fuel cost compared to the NG and MDO fuels. The PP was used to estimate the period required to recover the investment cost. The GT fuelled by NG and the diesel engine had the best PP compared to the GT fuelled by HYD.

Second Scenario:

The second scenario addressed CO_2 emissions taxes. The economic impact of an emissions tax depends on the CO_2 emissions from the propulsion systems; therefore, certain technology has an advantage over others when an emissions tax is applied. The CO_2 emissions tax was assumed to be the same for NG and MDO to determine the advantage of one propulsion system over the other. Regulations on CO_2 emissions were recommended by the Emissions Trading System, which is a cornerstone of the EU's policy for combating climate change. The carbon tax rates and years of implementation in European countries can be found in Figure 8 [58–62]. Figure 8 shows the carbon tax rate in each country.

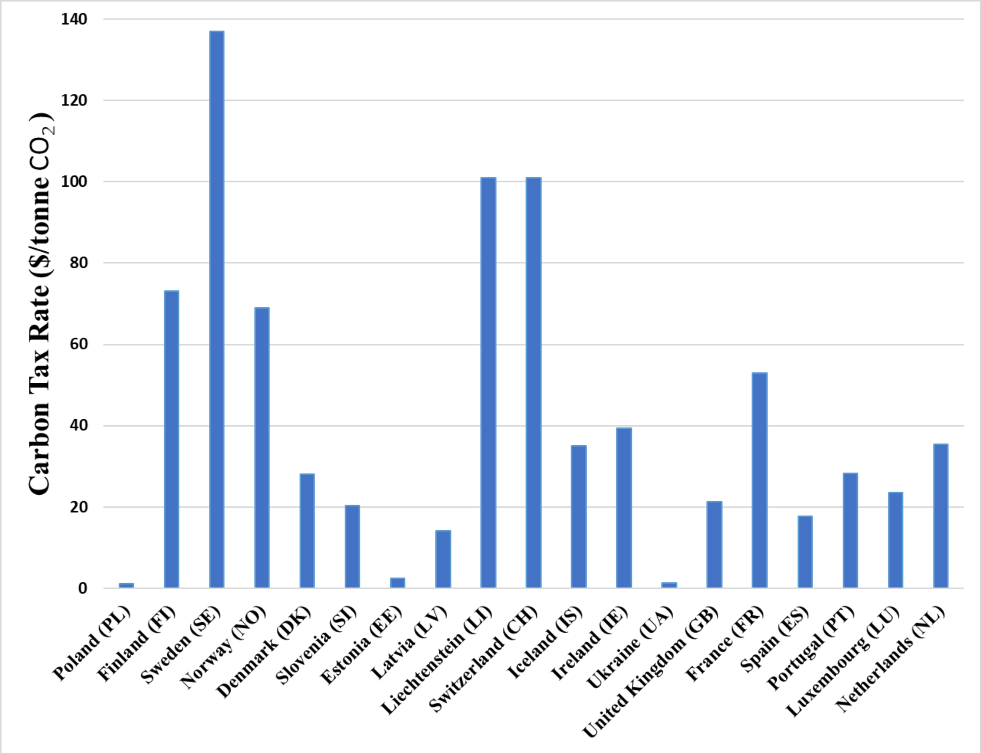

Figure 8. Carbon tax rate in European countries.

The average rate of the CO_2 tax of all EU countries was considered to be the CO_2 tax in this study. Figure 9 shows the change in the NPV between the first and second scenarios. When tax was applied, the results for the GT fuelled by HYD had greater relevance than those of the other technologies considered due to zero CO_2 being emitted from HYD. The results for the GT fuelled by NG and the diesel engine exhibited a high investment risk when a CO_2 tax was applied.

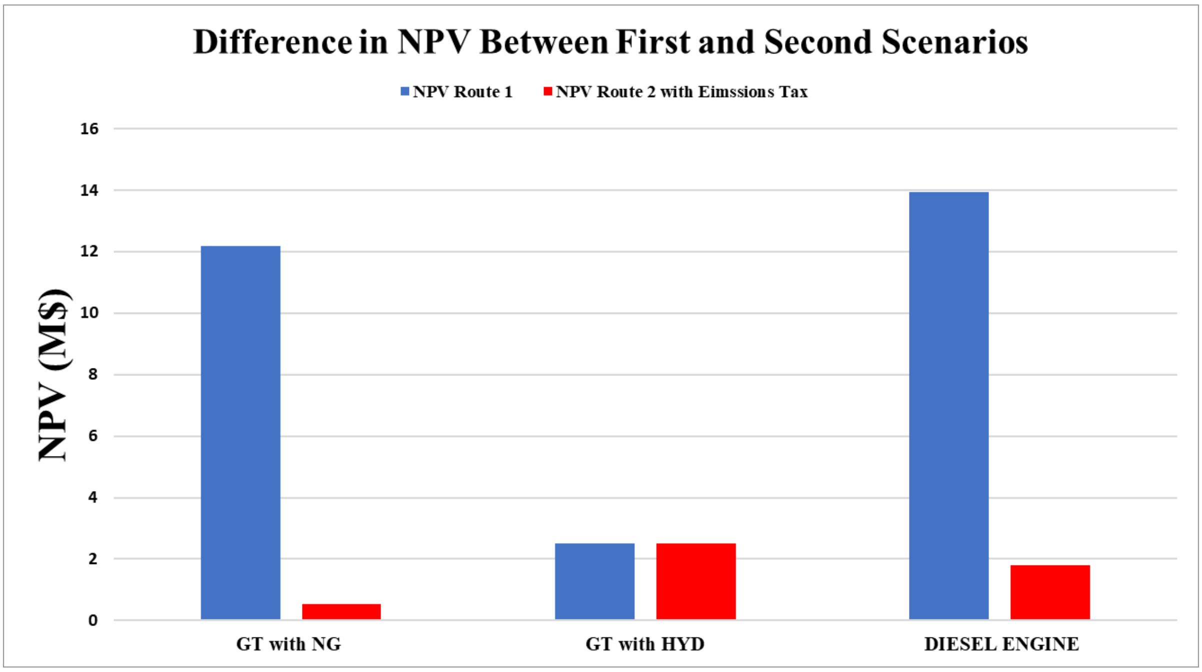

Figure 9. Net present value between the first and second scenarios.

Figure 10 shows the change in PP between the first and second scenarios. The highest period to return the investment was found for the GT cycles fuelled by NG and the diesel engine. The GT fuelled by HYD was promising when an emission tax was applied.

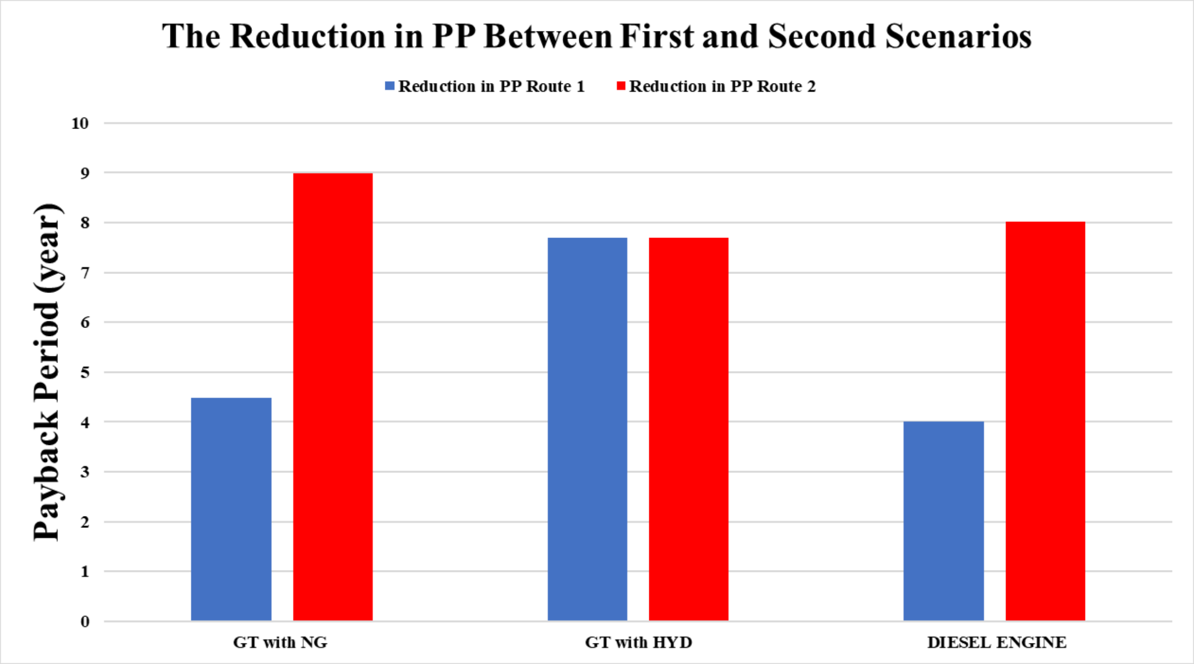

Figure 10. PP between the first and second scenarios.

4. Conclusions

In this study, a TERA method was employed to assess the advantages of using a gas turbine with cleaner fuel in RORO ships as a substitute for a diesel engine. A GT powered by natural gas and hydrogen, and a diesel engine fuelled by marine diesel oil (MDO) has been examined. The findings demonstrated promising economic benefits. The methodology was deemed valuable for engine selection and decision making. The key results of the study were as follows:

- The diesel engine emitted higher NOx emissions than the GT fuelled by NG and HYD by approximately 84% and 89%, respectively. The GT with HYD had zero CO_2 emissions, making it a viable option for sustainable energy production. The CO_2 emissions of the diesel engine fuelled with MDO were lower than the GT fuelled by NG by approximately 14%, owing to the higher efficiency of the diesel engine.
- Economic aspects were evaluated based on an international route. The economic profitability significantly relied on fuel cost and consumption.
- The first scenario revealed that the diesel engine fuelled by MDO and the GT fuelled by NG were economically attractive due to fuel cost and operating. The HYD-fuelled GT was less viable due to its high operating cost.
- The second scenario considered the effects of introducing a CO_2 tax on the economic analysis. For the routes considered and when a carbon dioxide tax was applied, the four-stroke diesel engine fuelled by marine diesel oil and GT fuelled with NG showed higher reductions in net present values; 86.4% and 90.4%, respectively. At the same time, the PP was increased by 44.4% and 50%, respectively. The results showed that the GT fuelled by HYD had potential as a substantial low-risk investment compared with the other technologies.

In conclusion, this study highlights that the TERA method is an indispensable tool in the maritime sector for comparing and selecting various propulsion systems. The limitation of the TERA method is data availability and quality; TERA relies on accurate and up-to-date data. A recommendation for future areas of research is larger or comparable studies assessing various kinds of vessels and different journeys to obtain more information about the optimal circumstances for the installation of GT and renewable energy propulsion technologies.

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