

## Article

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

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**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, we 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 liquefied 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, intercooler/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



**Citation:** Alzayed, A.M.T.; Sampath, S.; Pilidis, P. Techno–Economic and Risk Evaluation of Combined Cycle Propulsion Systems in Large Container Ships. *Energies* **2022**, *15*, 5178. <https://doi.org/10.3390/en15145178>

Academic Editors: Yuqiang Li, Gang Wu and Liyun Fan

Received: 15 June 2022

Accepted: 15 July 2022

Published: 17 July 2022

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## 1. 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<sub>x</sub>), sulphur oxides, and carbon dioxide (CO<sub>2</sub>) 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, CO<sub>2</sub>, NO<sub>x</sub>, 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.

## 2. 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 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].

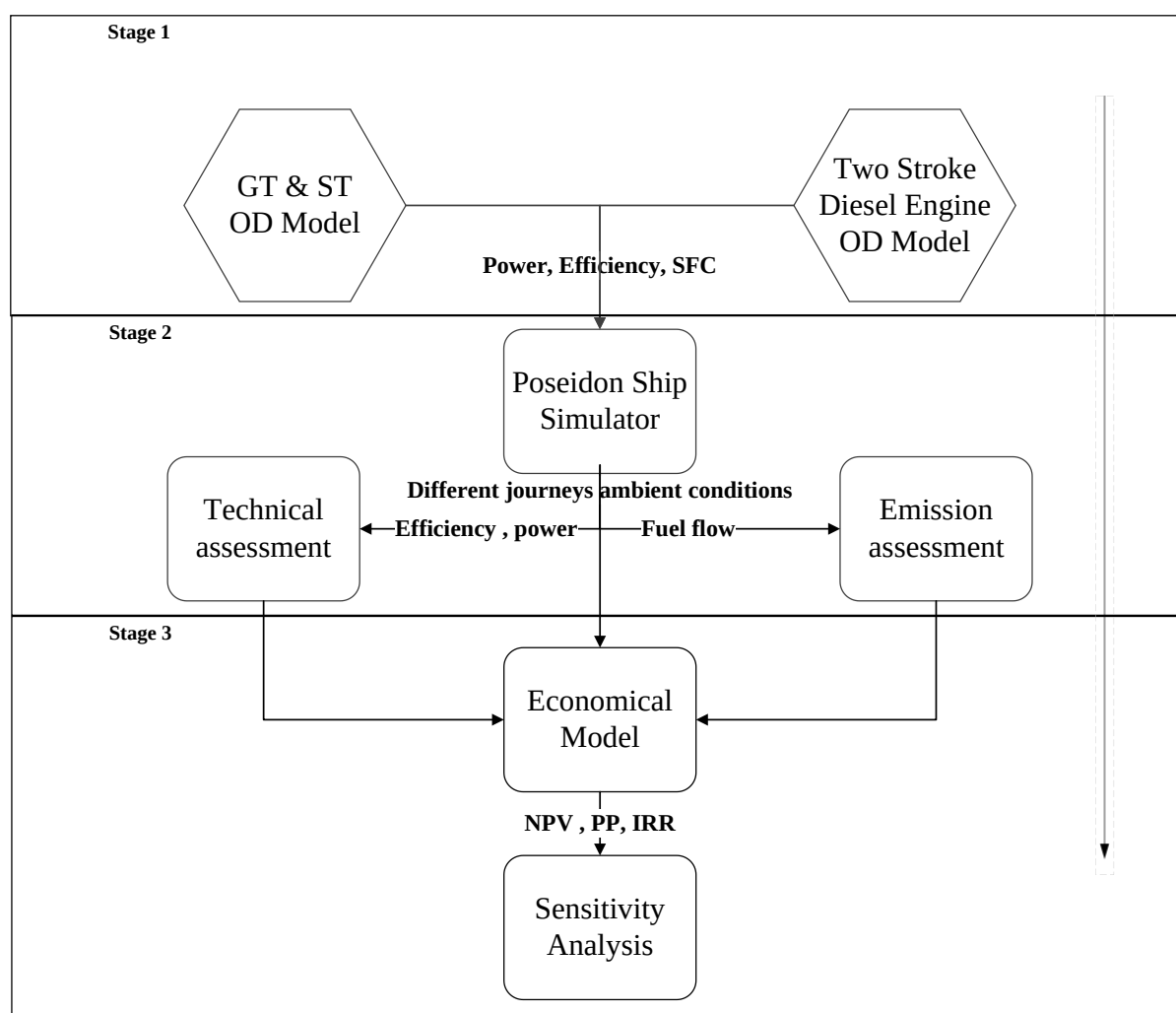


**Figure 1.** The framework of the methodology. GT: Gas turbine; ST: Steam turbine; OD: Off-design; NPV: Net present value; PP: Pay-back period; IRR: Internal rate of return.

### 2.1. Stage 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 our 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 1 lists the CCGT engines and their corresponding fuels.

**Table 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].

## 2.2. 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 roughness. 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<sub>x</sub> and CO<sub>2</sub> emissions from the CCGT and two-stroke diesel engine propulsion systems were also developed, as described in [11].

## 2.3. Stage Three Models

### 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]:

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

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]:

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

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:

$$PP = \frac{I_0}{C_o} \quad (3)$$

where  $I_0$  is the initial investment and  $C_o$  is the net annual cash inflow.

### 3. Results and Discussion

#### 3.1. Economic Analysis

Based on the scale and size of the technology and the information that is available in the literature, we 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 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 our previous study [10].

**Table 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 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 3, the global price of MDO [34,35] in (\$/tonne) was considered in this study.

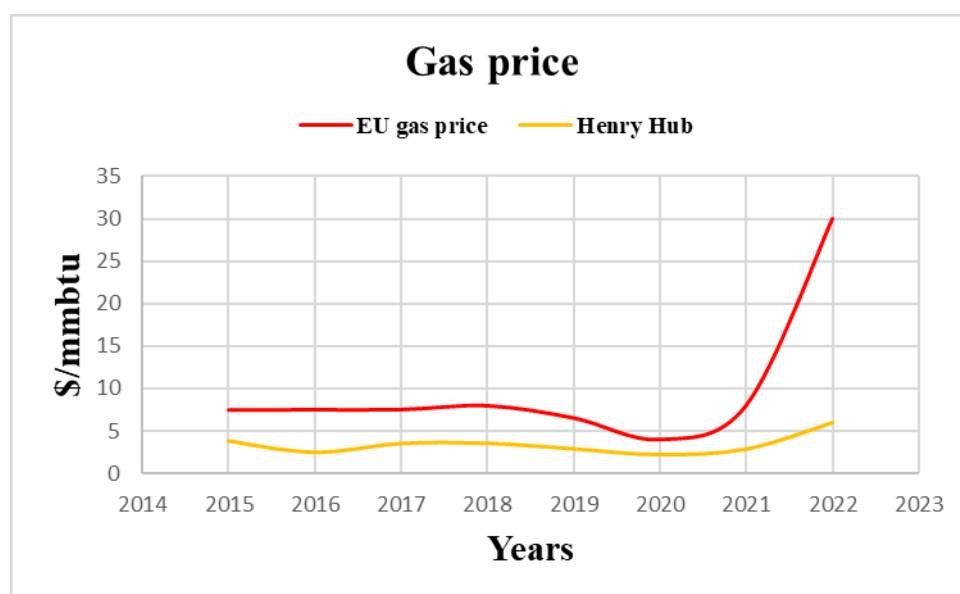


**Figure 2.** LNG prices in the European Union (EU) and Henry Hub markets.



**Figure 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 3.

**Table 3.** Average marine fuel prices.

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

Section 3.2 estimates 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 (nmi); and Route 2 was from Shanghai, China, to Hamburg, Germany, a distance of 10,778 nmi. 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.

### 3.2. The First Scenario

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

**Table 4.** Economic results for Route 1.

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

**Table 5.** Economic results for Route 2.

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

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 PPs 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 4.63 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 IRRs of 12%, 14%, and 13%, 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 6%, 5%, and 1%, 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.

### 3.3. The Second Scenario

The second scenario analyzes the effect of variations in the fuel cost (50% increase and 20% decrease). Figures 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.

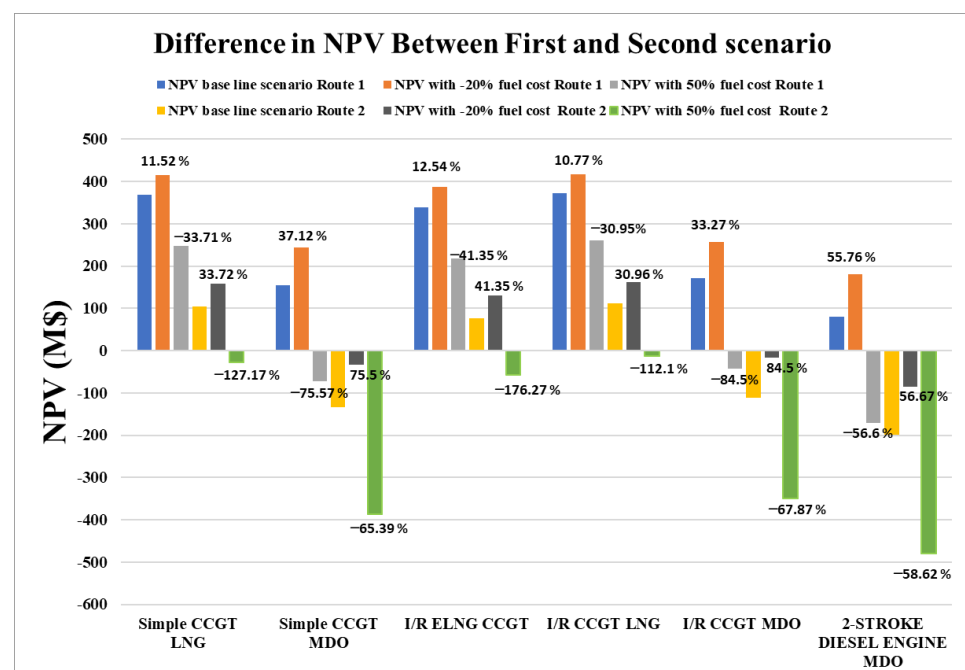


Figure 4. Difference in NPV between the first and second scenarios for Routes 1 and 2.

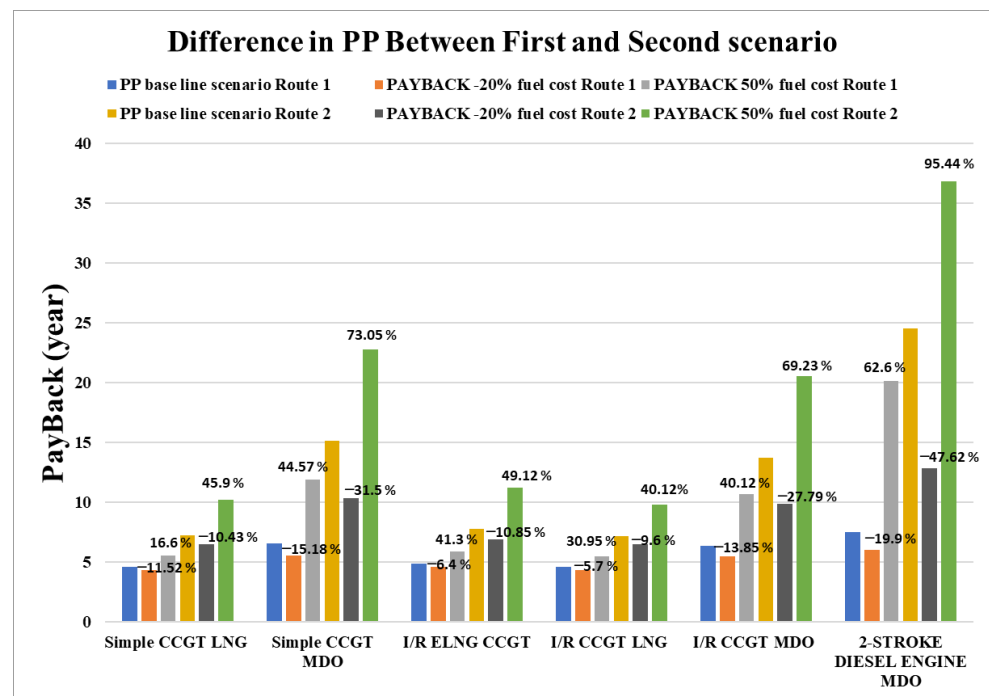


Figure 5. Difference in PP between the first and second scenarios for Routes 1 and 2.

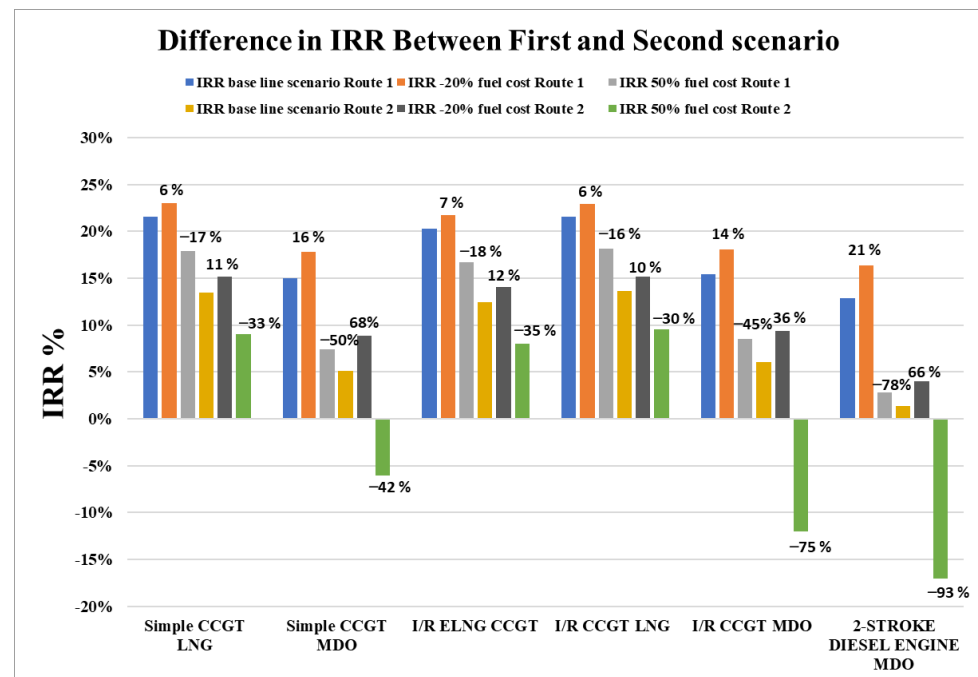


Figure 6. Difference in IRR between the first and second scenarios for Routes 1 and 2.

### 3.4. The Third Scenario

The third scenario analyzes the effect of variations in the capital cost (50% increase and 20% decrease). Figures 7–9 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 CCGT cycles show a higher impact regarding the higher capital cost compared with the two-stroke diesel engine.

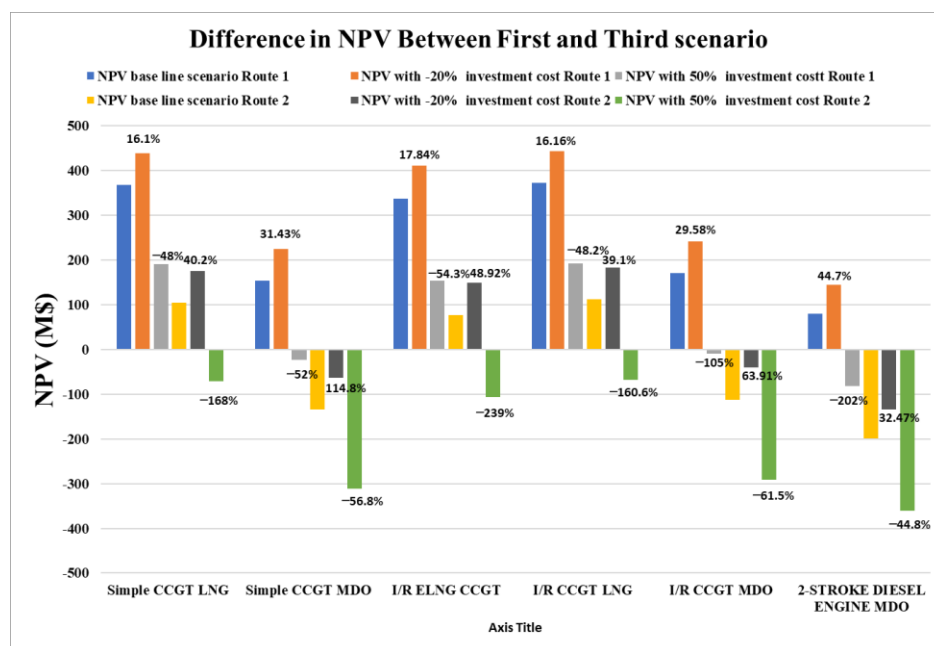


Figure 7. Difference in NPV between the first and third scenarios for Routes 1 and 2.

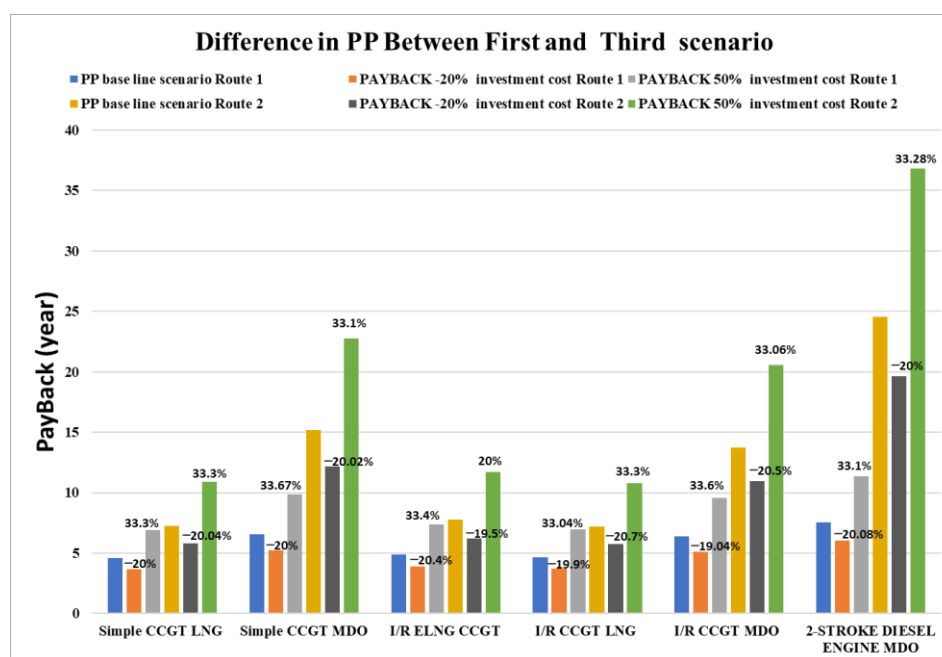


Figure 8. Difference in PP between the first and third scenarios for Routes 1 and 2.

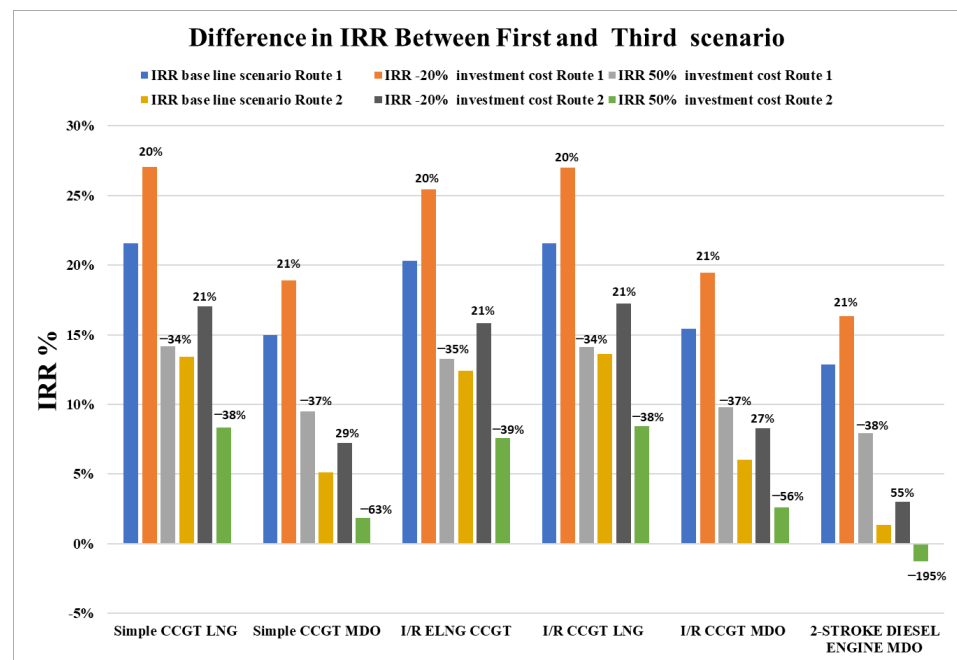


Figure 9. Difference in IRR between the first and third scenarios for Routes 1 and 2.

### 3.5. 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  $\mu\text{m}$  increase in the mean roughness amplitude [13]. The average hull roughness amplitude was assumed to gradually increase by 30  $\mu\text{m}$  every 15 y, with an initial clean hull roughness of 120  $\mu\text{m}$ . The method was tested by simulating a large container ship with a hull roughness of 120–180  $\mu\text{m}$ . 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 10–12 demonstrate the difference in NPV, PP, and IRR between the first and fourth scenarios for Routes 1 and 2.

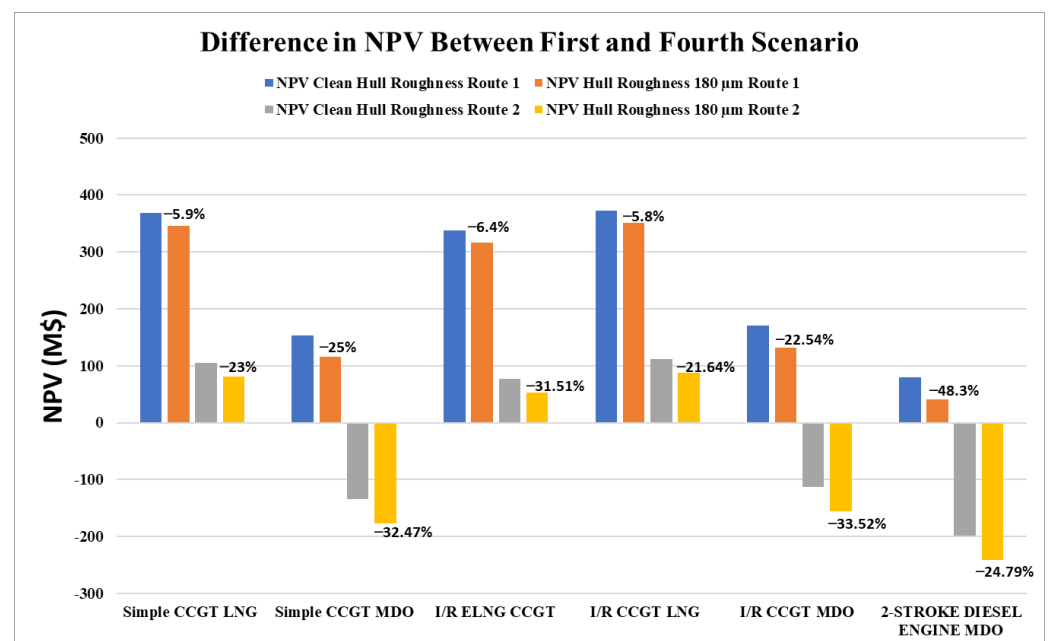


Figure 10. Difference in NPV between the first and fourth scenarios for Routes 1 and 2.

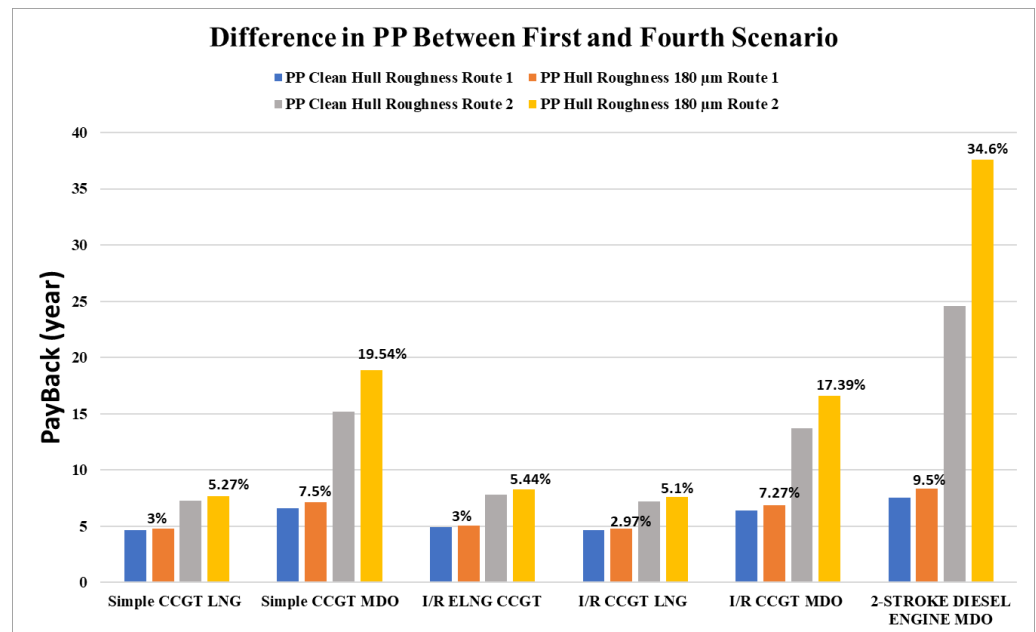


Figure 11. Difference in PP between the first and fourth scenarios for Routes 1 and 2.

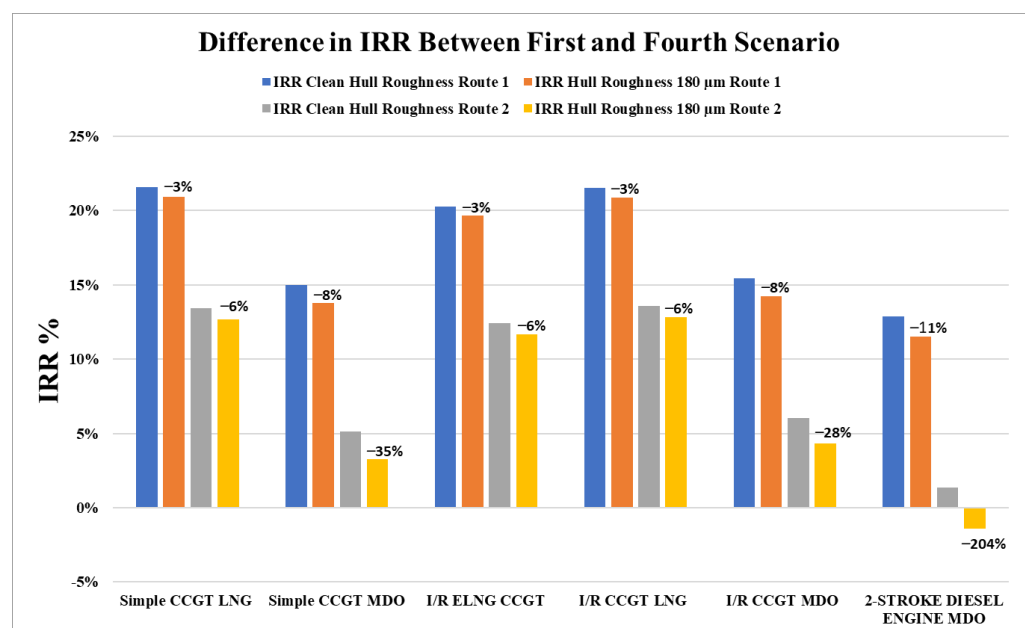


Figure 12. Difference in IRR between the first and fourth scenarios for Routes 1 and 2.

#### 4. Conclusions

Techno-economic and sensitivity 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 baseline 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.

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

**Funding:** This research received no external funding.

**Institutional Review Board Statement:** Not applicable.

**Informed Consent Statement:** Not applicable.

**Data Availability Statement:** Not applicable.

**Acknowledgments:** The authors are grateful to the Government of the State of Kuwait and the Public Authority for Applied Education and Training (PAAET) for their assistance and financial support.

**Conflicts of Interest:** The authors declare no conflict of interest.

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## **Techno–economic and risk evaluation of combined cycle propulsion systems in large container ships**

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**2022-07-17**

MDPI

<https://doi.org/10.3390/en15145178>

Alzayedi 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