Strategies for the Low Sulfur Policy of IMO—An Example of a Container Vessel Sailing through a European Route

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Abstract: Ships are an important part in international trade transportation and a major source of pollution. Therefore, the International Maritime Organization (IMO) implemented an amendment to the International Convention for the Prevention of Pollution from Ships (MARPOL) Annex VI, which stipulates that the sulfur content in marine fuel oil shall not exceed 0.5 wt.% starting in 2020. In order to meet the IMO low sulfur policy, shipping lines could adopt one of the following strategies: (1) using very low sulfur fuel oil (VLSFO), i.e., with sulfur content less than 0.5 wt.%; (2) installing scrubbers or other exhaust gas aftertreatment systems; or (3) replacing current fuels with clean alternative fuels such as natural gas. This study evaluates the feasibility and benefits of these strategies for shipping lines in order to determine the most cost-effective measures. First, according to the feasibility of the strategies evaluated by SWOT analysis, although scrubbers can reduce emissions of sulfur oxides into the atmosphere, more and more countries are restricting the discharge of wastewater from open-loop scrubbers into their waters. Instead, VLSFO and liquefied natural gas (LNG) are good choices in terms of environmental protection and economic benefits. Therefore, this study further evaluates the two strategies of replacing high sulfur fuel oil (HSFO) with VLSFO and converting diesel engines to LNG engines based on a cost-benefit methodology. This study took an 8500 TEU container vessel, which is powered by a marine diesel engine with the nominal power of 61,800 kW, sailing the Asian-European route as an example, and calculated the total incremental costs, pollutant emission reductions, and cost benefits arising from the implementation of the VLSFO and LNG strategies, respectively. According to the results of this study, the total incremental cost of LNG is higher than that of VLSFO in the first 4.7 years, but this gradually decreases, making the gap of the total incremental costs between the two strategies wider year by year. In comparison with using HSFO without any improvement, the total incremental costs of the VLSFO and LNG strategies increase by 12.94% and 22.16% over the following five years, respectively. The use of LNG can significantly reduce SOx, PM, NOx, and CO2 emissions; on the other hand, it leads to more CH4 emissions than the VLSFO strategy. Compared to doing nothing, the cumulative reduction rates of SOx, PM, NOx, and CO2 emissions over the next five years after the adoption of the LNG strategy are 3.6%, 7.0%, 70.4%, and 15.7%, respectively. The higher emission reduction rates of LNG compared to VLSFO illustrate that the former has a good effect on the suppression of exhaust gas pollution. In terms of the cost-benefit evaluation of the two strategies, this study shows that the VLSFO strategy is more cost-effective than the LNG strategy in the first 2.5 years, but that the cost-benefit ratio of the latter increases year by year and exceeds that of the former, and the gap between them widens year by year. Based on the evaluation results of this study, the LNG strategy is suitable for ocean-going container vessels with fixed routes and younger or larger sized vessels to meet the IMO low sulfur policy. In contrast, the VLSFO strategy is appropriate for old merchant ships with fewer container spaces. LNG is a suitable medium- and long-term strategy, i.e., for more than 2.5 years, for shipping lines to meet the IMO low sulfur policy, while VLSFO is a suitable short-term strategy.

Keywords: IMO low sulfur policy; very low sulfur fuel oil; liquefied natural gas (LNG); cost benefit; pollutant emissions
1. Introduction

With the rapid growth in global trade, the total greenhouse gas emissions from shipping increased by 9.6% from 977 million tons in 2012 to 10.76 million tons in 2018 [1]. According to a prediction by the International Maritime Organization (IMO), in 2050, CO$_2$ emissions arising from ocean transportation will account for 15% of global CO$_2$ emissions [2]. Under such circumstances, the shipping and shipbuilding industries face new challenges due to tightened emissions regulations. Hence, energy conservation and emission reduction are important concepts for the development of a green shipping industry. Meanwhile, 80% of global trade depends on sea transportation [3]. However, due to the large power of marine main engines and heavy fuel oil with poor quality as the main power source, greenhouse gas emissions from ships are considerable. Although shipping emits significant amounts of air pollutants and greenhouse gases, the percentage of the sector’s emission contribution to global totals is still low in comparison with those from land and air transportation. Hence, sea transportation is, by comparison, regarded as being relatively environmentally friendly [4].

Shipping is a major source of environmental pollution. The global shipping industry consumes about 330 million tons of marine fuel oil each year, of which 80% to 85% are high sulfur fuel oil (HSFO). Due to the long-term use of cheap, high sulfur, heavy residual oils as fuels, the exhaust gases produced by ships contain large amounts of pollutants, such as SOx and PM. According to the data in [5], a medium-sized container vessel operating continuously at 70% of nominal engine power emits the same amount of PM$_{2.5}$ (particulate matter with a diameter smaller than 2.5 $\mu$m) per unit time as 210,000 heavy trucks. Sulfur oxides (SOx) cause serious harm to health and to the environment [6]. The severe acidification of the ocean in the northern hemisphere is thought to be partly due to acid pollutant emissions from ships [7]. These pollutants may be contributing to climate change and cannot be ignored; additionally, they lead to acid rain and soil acidification [8]. Extreme climates are also associated with other pollutants such as sulfate aerosols and NOx [9]. Therefore, effective reduction measures of the hazardous pollutants emitted by ships are required.

The Marine Environmental Protection Committee (MEPC) of the IMO added an amendment to Annex VI of the International Convention for the Prevention of Pollution from Ships (briefly MARPOL) to limit sulfur content in heavy fuel oil. According to the policy, the sulfur content of fuel oil is required to be less than 0.5 wt.% for ships sailing in international waters, and less than 0.1 wt.% for those sailing in SOx emission control areas (SECAs), as of 2020. In order to comply with the IMO low sulfur policy and effectively reduce pollutant emissions from ships, shipping lines might choose one of the following strategies: (1) using very low sulfur fuel oil (VLSFO); (2) installing SOx scrubbers; or (3) using clean alternative fuels such as liquefied natural gas (LNG).

Regarding the above three strategies, ships adopting the first strategy require no refitting; however, the higher price of VLSFO increases operating costs, and low sulfur fuel increases wear on the main engine parts, as sulfur serves as a lubricant [10]. If the second strategy is adopted, while shipping lines can continue to use high sulfur fuel oil (HSFO) with low operating costs, they must invest 3–5 million USD for each ship to install scrubbers in the initial stage. The third strategy refers to replacing currently used HSFO with an alternative clean fuel, such as LNG or other clean or renewable fuel. Such fuels are significantly more environmentally friendly, effectively reducing emissions of SOx, NOx, particulate matter (PM) and CO$_2$ in the exhaust gas. In particular, LNG is a clean and low-carbon fuel. Each of the above three strategies has its advantages and disadvantages. Effective and objective evaluation methods are therefore required to choose the best strategies to bring shipping activities in line with MARPOL regulations.

Previous studies have focused on evaluations of individual strategies, such as analyzing the advantages and disadvantages of each strategy, the main challenges and obstacles in implementing emission reduction measures, and potential factors in strategy promotion through the triangulation research approach [2]. Some studies have analyzed SOx
emissions reductions using VLSFO through the fuzzy analytic hierarchy process (AHP) method [11], while others have evaluated the effects of SOx scrubbers used by merchant ships on pollutant emission reduction [12–14]. There is also literature on the various equipment needs and operating costs arising from addressing the technical difficulties associated with the use of VLSFO for marine engines [13,15–19]. The performance difference between a LNG-heavy oil, dual-fuel powered ship converted from a passenger ship powered by heavy fuel oil was investigated in [20]. The question of whether the market is willing to pay a high premium for LNG-fueled ships was addressed in [21]. However, few studies have analyzed and compared the increased costs and pollutant emission reductions among the various strategies which have already been implemented. In particular, no report has evaluated a potential strategy based on the cost-benefit ratios of all possible strategies.

As one of the most important type of merchant ships, container vessels sail to various ports around the world, carrying and delivering cargo. Hence, their shipping hours and nautical miles are much larger than those of other types of merchant ships. As such, they are responsible for relatively much larger amounts of pollutant emissions than other types of marine vessels, and thus, have greater effects on global air quality. In 2011, the world’s top 10 container shipping lines comprised about 62% of the total global shipping capacity; this figure had increased to 75% by 2017 [22]. Moreover, container vessels consume the largest amount of heavy fuel oil among all types of merchant ships. Therefore, according to the IMO policy on reducing pollutant emissions from ships, this study comprehensively evaluates feasible strategies by comparing their total incremental costs, pollutant emission reductions, and cost-benefit ratios. The advantages and disadvantages of the various feasible strategies, as well as the difficulties and challenges associated with their implementation, are systematically assessed. The methods of SWOT (i.e., Strengths, Weaknesses, Opportunities, and Threats) analysis and cost-benefit ratio analysis are first applied to investigate strategies seeking to address the low fuel-sulfur policy of the IMO. A container vessel powered by a traditional diesel engine on an ocean-going Asian-European route, operated by one of the world’s top 10 container shipping lines (Y shipping line for short), [23] was taken as the subject vessel. The evaluation method and results of this study may serve as a valuable reference for shipping lines and academics in related fields to determine strategies or pursue further academic research.

2. SWOT Analysis on Feasible Strategies

Ocean-going container vessels generally use high sulfur fuel oil (HSFO). In order to meet the IMO policy on reducing pollutant emissions from ships, this study proposes three feasible strategies, i.e., installing scrubbers, using VLSFO, or using LNG fuel, which are hereafter referred to as Scrubber strategy, VLSFO strategy, and LNG strategy, as shown in Table 1.

| Strategy   | Description                                                                 |
|------------|-----------------------------------------------------------------------------|
| Scrubber   | Install scrubbers in exhaust systems of main engine and continue to use HSFO (S \(\leq 3.5\) wt.\%) |
| VLSFO (S \(\leq 0.5\) wt.\%) | Change HSFO to VLSFO                                                  |
| LNG        | Use LNG as an alternative fuel for HSFO                                    |

This study first evaluated the feasibility of the above three strategies by strengths, weaknesses, opportunities, and threats (SWOT) analysis. The results of the SWOT analysis for the three strategies are shown in Table 2.
### Table 2. Results of SWOT analysis of three feasible strategies.

| Indicator | Scrubber | VLSFO | LNG |
|-----------|----------|-------|-----|
| **Strength** | Effective reduction of more than 90% of SOx emissions in the initial stage | Small refit, low initial cost, Low SOx emissions. | Low pollutant emissions, Reduction in ship operating costs, High thermal efficiency, Long service life and low maintenance costs for machines, In compliance with international emission standards. |
| **Weakness** | High initial costs for installation, Large container space occupied by scrubbers, Open-loop systems applicable for limited waters, Equipment deteriorates with usage, and reduces emission reduction effects | Significant increase in operating costs, Cylinder liners wear out more frequently, Poor ignition quality, Change of lubrication oil, Low viscosity, Incompatibility | High additional investment costs, Special training is required for crew members. |
| **Opportunity** | Widening gap between prices of high and low sulfur fuels, | Falling prices for lubricant and fuel additives, | Lower price than VLSFO. |
| **Threat** | Prohibition of open-loop systems at some ports, Maintenance and continuous deterioration of scrubbers. | Indeterminacy in fuel price. | Poor infrastructure, such as gas refueling ports, Pollution caused by incomplete combustion of CH₄ |

According to Table 2, if the Scrubber strategy is adopted, as it is necessary to invest in ship refitting and scrubbers, the initial investment will be high [24]. In addition, scrubbers will take up cargo space, resulting in operating loss due to permanent occupancy of shipping space. Open-loop scrubbers are explicitly prohibited at some ports, which is a fatal weakness for this strategy. However, since ships can continue to use high sulfur fuel oil after scrubbers have been installed, the lower price of high sulfur fuel oil becomes the biggest strength of this strategy. If the VLSFO strategy is adopted, as no special refitting is required, the initial investment will be low. However, due to the low sulfur content in fuel oil, if engine parts are not sufficiently lubricated, VLSFO will cause cylinder liner abrasion and even breakages [11,25]. In addition, the operating costs of the VLSFO strategy increase due to the unclear future price appropriate fuels [24].

The biggest strength of the LNG strategy is that it emits significantly fewer pollutants than the VLSFO and Scrubber Strategies. Based on a case study of a high-speed passenger ship, after conventional diesel is replaced with natural gas, NOx, SOx, PM, and CO₂ emissions can be reduced by 72%, 91%, 85%, and 10% [26], respectively. Moreover, as LNG is cheaper than VLSFO, it helps to reduce operating costs [27,28]. However, the high pressure tank used to store LNG on ships requires about 2–2.5 times more space than a diesel fuel tank with equivalent power [29]. In addition, the construction cost of an LNG tank on ships is about 8–20% greater than one for diesel [11]. More importantly, with the exception of northern Europe, at many ports around the world, LNG refueling is not provided, or the LNG refueling infrastructure is not perfect [30], which makes it difficult to load, store, and transport LNG. Hence, the routes for LNG-fueled ships are currently limited. The decision of shipping lines to use LNG might depend on three main factors: the price difference between LNG and VLSFO, the continued tightening of global emissions regulations, and the number of ports with LNG refueling facilities [31]. According to information from DNV.GL [32], as of 24 August 2021, globally, there were 568 LNG-fueled ships in service and 199 under design, accounting for 10.58% and 3.7% of the global total of 5371 container vessels, respectively. Therefore, the proportion of LNG-fueled ships is steadily increasing. The 72 LNG-fueled container vessels currently under construction [32] indicate the huge potential for the future development of LNG-fueled ships [33].
Even though it has a higher initial investment than the LNG strategy, the Scrubber strategy is currently the most popular model, as high sulfur fuel oil can continue to be used after the installation of scrubbers. There are three types of scrubbers: open-loop, closed-loop, and hybrid. For closed-loop scrubbers, the toxic waste which is generated needs to be treated at high cost, and the treated waste must be temporarily stored on the ship and entrusted to a waste treatment company at the next port for further treatment. Open-loop scrubbers use seawater as an absorbent to remove sulfur oxides from the exhaust gas. However, acidic wastewater containing various pollutants is discharged into the sea, which causes pollution to the marine environment. In addition, scrubbers deteriorate gradually as they age, which weakens their emission reduction effects. Therefore, from the perspective of environmental protection and sustainable operation, the Scrubber strategy is considered to be inferior. According to our comprehensive evaluation and analysis of the three aforementioned strategies, as shown in Table 2, the LNG and VLSFO Strategies are the most sustainable and environmentally-friendly. Therefore, this study will describe a cost-benefit analysis for these two strategies in the following section.

3. Characteristics and Challenges of LNG Powered Ships

3.1. LNG Dual-Fuel Engine Technology

Liquefied natural gas (LNG) is mainly composed of colorless, odorless, nontoxic, and noncorrosive methane, i.e., 80–99% methane (CH₄), a small amount of ethane (C₂H₆), propane (C₃H₈), butane (C₄H₁₀), pentane (C₅H₁₂), and some inert gases, such as carbon dioxide (CO₂) and nitrogen (N₂). The exact composition of natural gas varies with the origin, time, and treating process. The specific gravity of natural gas is about 0.58–0.79 times that of air. Upon cooling to −162 °C at atmospheric pressure, natural gas is converted into a liquid state, namely, LNG, which is considered one of the cleanest fossil energy sources on earth [34]. LNG is not only clean and environmentally friendly, but also economically advantageous. At the same calorific value released from complete fuel burning, LNG is cheaper than very low sulfur fuel oil (VLSFO).

Given the superior antiknocking properties of natural gas due to its high octane number, as well as its poor compression-ignition characteristics owing its low cetane number, current natural gas engine technologies mainly comprise one of the following designs: spark-ignition lean-burn, spark-ignition stoichiometric combustion, and compression-ignition dual-fuel [34–36]. The features, advantages, and disadvantages of these three engine technologies are shown in Table 3:

| Item                      | Spark-Ignition Lean-Burn Design | Spark-Ignition Stoichiometric Combustion Design | Compression-Ignition Dual-Fuel Design |
|---------------------------|---------------------------------|-----------------------------------------------|-------------------------------------|
| Feature                   | Uses a single fuel, i.e., natural gas. | Uses a single fuel, i.e., natural gas; Uses a stoichiometric air/fuel mixture ratio. | Uses dual fuels comprising natural gas and diesel; Requires ignition of pilot injection; |
| Advantage                 | Low flame and exhaust gas temperature; Low HC, CO, and NOx emissions; High thermal efficiency; Improved service life and reliability of machines. | Similar to light load gasoline engine technology; High degree of combustion reaction. | Simple and cheap refitted diesel engine. Flexible use of natural gas; Lower pollutant emissions than simple diesel engines. |
| Disadvantage              | Avoids misfires and discontinuous combustion. | Needs a catalytic converter and air-fuel ratio control systems; Low thermal efficiency. | High HC and CO emissions, and efficiency degradation at low load. Requires accurate control of the flow rates of two fuels simultaneously; Requires two fuel feeding systems and two separate fuel tanks. |

Source: Compiled by the authors from [34–36].
With a compression-ignition dual-fuel engine design, most diesel engines can be refitted into diesel-natural gas dual fuel systems. After the intake manifolds inject the pre-mixed natural gas and air into the combustion chambers, the fuel mixture is ignited by pilot diesel fuel. Dual fuel engines use diesel fuel as a polite fuel to ignite the natural gas. Dual-fuel engines can reduce diesel consumption by 70–99% compared to conventional diesel engines. However, if the natural gas is used up, the engine can still run with diesel. As such, dual-fuel engines are flexible in terms of fuel type, which is conducive to ship navigation. The dual-fuel engine design can maintain the existing diesel engine architecture, and requires no significant refitting. Therefore, this study intends to convert the engine of an ocean-going container vessel originally powered by a compression-ignition diesel engine into an LNG-diesel dual fuel engine.

3.2. LNG Refueling Facilities at International Ports

LNG has different characteristics from HSFO or VLSFO. For example, it requires a safe delivery method. In order to refuel ships with LNG, it is important to comply with the regulations of the local port authorities and obtain permission from the authorities of port states. Refueling ships with LNG is subject to IMO IGC (International Gas Code), while LNG fueling is subject to the IMO IGF (International Gas Fuel) Code. Currently, there are three methods to refuel LNG-fueled ships, as shown in Table 4 and explained below.

| Item | TTS | STS | PTS |
|------|-----|-----|-----|
| **Advantages** | Low requirement for infrastructure and relatively low investment costs; Trucks can be used for LNG distribution for other purposes. | Able to be carried out at various places (e.g., ports and anchorage grounds); Highly flexible in capacity and refueling locations. | High refueling rate, which reduces refueling time. |
| **Disadvantages** | Limited truck capacity, which is only suitable for a small amount of LNG delivery; Trucks and refueling process will affect other activities at ports. | High investment costs for refueling ships | Low maneuverability; Berthing restrictions for large ships may be an obstacle. |
| **Types of ships** | Most suitable for LNG-fueled ships with lower fuel capacities, such as tugboats, inland ships, coast-guard ships, and small passenger ships. | The most common refueling method for ocean-going ships; Underway replenishment is suitable for all types of ships | Suitable for shipping services with high refueling frequency, small demands, flexible shipping schedule, and limited ship draft. |

Source: Compiled by the authors from [37].

1. Truck-to-Ship (TTS): a truck is connected to an LNG receiving ship at the port for fuel delivery through a flexible hose, usually assisted by a manual cantilever crane.
2. Ship-to-Ship (STS): LNG is delivered to the receiving ship by another ship or barge anchored opposite in the port.
3. Port-to-Ship (PTS): an LNG-fueled ship can be refueled directly from a small LNG storage unit (LNG tank), small gas refueling station, or LNG output terminal at the port.

Different LNG refueling methods can meet different needs, depending on the amount of LNG to be refueled and the operation time; for example, if only a small amount of LNG is required, TTS is suitable; otherwise, STS or PTS could be adopted. PTS or STS are the most suitable LNG refueling methods for large ocean-going merchant ships. Currently, most of the world’s LNG refueling stations are located in Rotterdam, Hammerfest, Barcelona, and Hamburg in Europe, Montreal, Jacksonville, Port Fourchon, and Panama in the Americas, and in a few Asian ports, such as Singapore, Kochi, Yokohama, and Busan. Malaysia’s first STS LNG refueling facility was completed at Port Klang in July 2021. As LNG refueling can be carried out at two ports (Rotterdam and Singapore) on the route discussed in this study, the LNG quantity can cover the entire voyage without additional refueling at other ports.
4. Cost-Benefit Ratio Calculation Method

This study focuses on an 8500-TEU container vessel (termed Vessel A hereafter) on the Asian-European route operated by Y shipping line [22], which is one of the world’s top 10 container shipping lines. This vessel was powered by high sulfur fuel oil (HSFO) until 2020. In order to compare and explore the development potential and cost benefit of LNG-powered ships on the European route, we assumed that the vessel had been converted to an LNG-powered vessel (named Vessel B). In our study, VLSFO and LNG fuels were used for the vessels, which are denoted as the VLSFO and LNG strategies respectively. This study calculated and compared the incremental costs, pollution reductions, and cost-benefit ratios of the container vessels powered by different fuels against the benchmark of a high sulfur fuel oil ship. The container vessel of the Y shipping line was built in 2018, with 76 days per voyage and five annual voyages. The nominal power of its main engine at 90.8 rpm is 84,024 PS (i.e., 61,800 kW). The particulars of this vessel are shown in Table 5.

Table 5. Particulars of container Vessel A.

| Particulars                                      | Details                   |
|-------------------------------------------------|---------------------------|
| Built Year                                      | 2018                      |
| Total Capacity                                  | 8500 TEU                  |
| MCR (Maximum continuous rating)                 | 93,360 PS at 94 rpm       |
| NCR (Normal continuous rating)                  | 84,024 PS (61,800 kW) at 90.8 rpm |
| Fuel oil consumption rate                        | 171.8 g/kWh               |
| Route                                           | Asian-European Service    |
| Number of days per voyage                        | 76 days                   |
| Number of annual voyages                        | 5                         |
| Full-speed sailing hours                         | 5660 h/year               |
| Fuel tank capacity                               | 8000 m³                   |

For vessels sailing among international ports, there are roughly three legs for the voyage, from the berth at the port of departure to open water, a voyage in open water, and from open water to the berth at the port of destination. On the second leg, the vessel’s main engine commonly runs at the most economic speed, and the engine speed will not be deliberately increased or decreased if there is no emergency. During the first and third legs of the voyage, the operating load on the main engine may vary from voyage to voyage due to various factors (such as waiting for the berth in the berthing area, or sailing within the speed limit). This study explored the cost benefits of two practical strategies (i.e., VLSFO and LNG), where the actual full-speed sailing hours are taken as the basis for our evaluation. Therefore, in this study, the actual full-speed sailing hours (5660 h/year) of the container vessels on this route were taken as the annual full-speed sailing hours of Vessels A and B.

This study considers that Vessels A and B on the European route head west from Tianjin in China to Antwerp. The vessels sail through Shanghai Port, Ningbo Port, Yantian Port, Singapore Port, Colombo, and the Suez Canal, and then return to Tianjin via Rotterdam, Hamburg, and Port Klang in Malaysia. All ports on the European route are shown in Figure 1, where the red solid line indicates the westward route from Tianjin to Antwerp, while the blue solid line indicates the eastward route back from European ports to China. The round trip is about 23,972 nautical miles (NM), where 1 NM = 1.852 km. The distances between berthing ports on this route are shown in Table 6; for example, the distance from Tianjin to Shanghai is 686 NM, and from Singapore to Colombo is 1626 NM. The shipping route starting from Tianjin through Colombo to Antwerp mostly sails in the ocean region outside the designated emission control region. The vessel only sails a short distance through the sulfur emission control area (SECA), i.e., only to about 3% of the total sailing route. Hence, sailing through SECA is not considered in the cost calculation in the present study.
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Figure 1. European route of this study.

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Table 6. Distance between berthing ports on this route. Unit: NM.

| Berthing Port | Tianjin | Shanghai | Ningbo | Yantian | Singapore | Colombo | Antwerp | Hamburg | Rotterdam | Port Klang | Tianjin |
|---------------|---------|----------|--------|---------|-----------|---------|--------|---------|-----------|-----------|---------|
| Distance between ports | 0       | 686      | 172    | 735     | 1469      | 1622    | 7313   | 405     | 314       | 8293      | 2959    |

4.1. Definitions of Cost Items and Estimations of Total Incremental Costs

Cost is defined as the economic value in monetary terms of the resources consumed in producing and selling a certain type and quantity of products. It refers to the expenditures required in this study to implement a suitable strategy. This study estimates and compares the incremental costs of different strategies. The method of incremental costing [38] is considered appropriate for adoption based on many cost calculations.

In order to comply with the MARPOL, Vessels A and B were compared on the same shipping route, where Vessel A is powered by VLSFO and Vessel B by LNG. The total incremental costs, pollutant emission reductions, and cost benefits arising from the annual shipping operations of both vessels in contrast to those of a vessel powered by HSFO were calculated. Therefore, this section explains all cost items which were taken into consideration, as well as their calculation methods, and then, calculates and evaluates the total incremental costs of Vessels A and B.

The incremental cost items include the cost of refitting a diesel engine into an LNG-powered engine, operating losses due to refitting the LNG engine, crew wages during LNG equipment installation, price difference between HSFO and LNG, amount of LNG consumption for vessel sailing, and loss of shipping space due to LNG storage tank installation, etc. The fuel consumed by vessels is related to the performance of the primary marine engines, vessel size, full-speed sailing hours, and navigation distance. The cost items were classified into capital expenditures (CAPEX) and operating expenses (OPEX), and the total cost was obtained by adding CAPEX to OPEX. The cost items required by Strategies VLSFO and LNG are shown in Table 7.
The methods used to calculate the total incremental costs of the VLSFO and LNG strategies were as follows.

4.1.1. Calculation Method for the Total Incremental Cost of the VLSFO strategy

The total incremental cost of Vessel A after the adoption of the VLSFO strategy consists of OPEX and CAPEX, as shown in Equation (1):

\[ y = a + b \]  

(1)

where \( y \), \( a \) and \( b \) denote (Total incremental cost)\textsubscript{VLSFO}, (OPEX)\textsubscript{VLSFO}, and (CAPEX)\textsubscript{VLSFO}, respectively. The subscript VLSFO indicates that vessel A adopts the strategy with VLSFO as the fuel. The method to calculate (OPEX)\textsubscript{VLSFO} is shown in Equation (2), including fuel additive cost and environmental fuel fee (EFE).

\[ a = c + d - e \]  

(2)

where \( a \), \( c \), \( d \) and \( e \) represent (OPEX)\textsubscript{VLSFO}, price difference between VLSFO and HSFO, fuel additive cost, and environmental fuel fee, respectively.

Fuel costs account for about 60% [39–42] or even 80% [22] of the overall operating cost of a shipping line, which is very high. Therefore, shipping lines are deeply concerned about fluctuations in oil prices. As VLSFO and LNG prices fluctuate with the international price of crude oil, this study refers to LNG and crude oil price forecasts from 2022 to 2026, taken from the Knoema website [43], which is a global data and atlas analysis platform. The predicted LNG prices based on the Knoema website [43] and according to the U.S. Energy Information Administration [44] are around 5.35–6.25 USD/MMBtu and 4.73–6.09 USD/MMBtu, respectively. Hence, the global LNG price is expected to be stable, and as such, no significant LNG price fluctuations were factored into the cost calculations in this study. In addition, according to the Ship & Bunker website [45], the price of VLSFO is about 26% higher than that of crude oil per ton. On this basis, this study estimated the LNG and VLSFO prices from 2022 to 2026 (as shown in Figure 2) as the annual prices of LNG and VLSFO (in USD/ton) over the next five years, following the implementation of the two strategies for the IMO low sulfur policy, as shown in Figure 2. The sulfur content of VLSFO is less than 0.5 wt.%. The annual cost of high sulfur fuel oil (HSFO) can be calculated by Equation (3).

\[ f = g \times h \times i \times j \times 10^{-6} \text{ ton/g} \]  

(3)
where \( f, g, h, i \) and \( j \) denote total fuel oil cost, fuel consumption rate (g/kWh), annual high sulfur fuel oil price (USD/ton), full-speed sailing hours (h/year), and output power of the main engine (kW), respectively.

In Equation (2), the fuel oil price difference arising from Vessel A adopting the VLSFO strategy sailing on the Asian-European route in one year is calculated by Equation (4):

\[
c = g \times k \times i \times j \times 10^{-6} \text{ ton/g}
\]

where \( c, g, k, i \) and \( j \) represent cost difference between VLSFO and HSFO (USD/year), fuel consumption rate (g/kWh), \([\text{VLSFO price} - \text{HSFO price}] \) (USD/ton), full-speed sailing hours (h/year), and output power of the main engine (kW), respectively.

In Equation (2), the sulfur content is greatly reduced in VLSFO in order to reduce SOx emissions. However, fuel sulfur acts as a lubricant in fuel oil. If the sulfur content is below 0.5 wt.%, increased abrasion of the cylinder liner and the pump plunger will occur, leading to engine gas leakage and even break downs. The reduced lubrication of VLSFO can be solved through the use of appropriate lubricating additives. According to the experiment, by adding 3% bio-oil to fuel oil, its lubrication effects are as good as those of HSFO [46,47]. Therefore, in this study, the bio-oil price is used for the lubricant additive cost for VLSFO. According to [48], the biomass oil price is 1245.9 USD/ton. In this study, it is assumed that the biomass oil prices will decrease by 5% year by year due to the continuous evolution of bio-oil manufacturing technology.

The environmental fuel fee (EFF) in Equation (2) refers to the short-term, variable, or seasonal surcharge paid by shipping lines according to the fuel oil market price. EFF is charged due to increases in VLSFO fuel oil costs, in order to comply with the international MARPOL convention [49]. The fee varies greatly according to the route and the type and size of the vessel. The average EFF for each TEU (Twenty-Foot Equivalent Unit) container is around USD 30 to USD 80, and that for each FEU (Forty-Foot Equivalent Unit) container is roughly double that amount. Reefer (i.e., refrigerated) containers are subject to an increased fee because their generators consume more energy than general purpose containers. As EFF is usually about 10% of the VLSFO price, this study takes 10% of the fluctuating VLSFO price as the EFF per TEU per voyage. Therefore, as Vessel A sails five voyages per year, the annual EFF is calculated as shown in Equation (5).

\[
e = m \times n \times 2 \times p
\]

where \( e, m, n, \) and \( p \) denote EFF per year (USD/year), number of TEU of containers, EFF per TEU (USD/TEU), and number of voyages/year, respectively. The multiplication by 2 in the above equation is because each voyage consists of two legs, namely, departure and return.
Since Vessel A, which adopted the VLSFO strategy, uses a marine diesel engine, there is no need to modify or add any engine or storage tank. Hence, \((\text{CAPEX})_{\text{VLSFO}}\) (i.e., the term \(b\)) in Equation (1) is 0.

### 4.1.2. Calculation Method for the Total Incremental Cost of the LNG Strategy

Vessel B adopted the LNG strategy. In addition to the fuel price of LNG, costs of infrastructure for natural gas liquefaction and storage shall be considered. The method to calculate the total incremental cost of the strategy is shown in Equation (6).

\[
q = r + s
\]

where \(q\), \(r\) and \(s\) represent \((\text{total incremental cost})_{\text{LNG}}, \ (\text{OPEX})_{\text{LNG}}, \) and \((\text{CAPEX})_{\text{LNG}}, \) respectively. In the above equation, the subscript LNG indicates that Vessel B adopted the strategy with LNG as the fuel. According to Table 7, the OPEX of the LNG strategy includes the price difference between HSFO and LNG, maintenance costs of LNG equipment, loss of shipping space due to LNG equipment installation, the wage premium for crew operating LNG equipment, a penalty for pilot fuel consumption, and a penalty for the use of a cryogenic pump fuel. The method to calculate \((\text{OPEX})_{\text{LNG}}\) is shown in Equation (7).

\[
r = t + u + v + w + x + y
\]

where \(r\), \(t\), \(u\), \(v\), \(w\), \(x\), and \(y\) denote \((\text{OPEX})_{\text{LNG}}, \) price difference between HSFO and LNG, maintenance cost of LNG equipment, loss of shipping space due to LNG equipment installation, wage premium for crew operating LNG equipment, penalty for pilot fuel consumption, and penalty for the use of a cryogenic pump fuel, respectively. In the above equation, the fuel oil price difference arising from Vessel B fueled by LNG sailing on the Asian-European route in one year is calculated by Equation (8).

\[
t = l \times z \times i \times j \times 10^{-6} \text{ ton/g}
\]

where \(l\), \(z\), \(i\), and \(j\) represent cost difference between HSFO and LNG (USD/year), [LNG price—HSFO price] (USD/ton), full-speed sailing hours (h/year), and output power of main engine (kW), respectively.

In Equation (7), the methods to calculate other operating costs are described as follows:

1. Maintenance cost of LNG equipment: as LNG is a cleaner fuel than VLSFO, the main engine maintenance costs will be reduced by about 40% compared with the previous situation, i.e., using HSFO [26].

2. Loss of shipping space due to LNG equipment installation: an LNG storage tank is about 2–2.5 times the size of a fuel oil tank for the same engine power output [29]. As shown in Table 6, the fuel oil tank of Vessel A is 8000 m\(^3\); thus, it can be calculated that Vessel B fueled by LNG loses about 410 TEU of shipping space. Figure 3 shows the average container shipping cost for the Asian-European service loop route according to the report of the United Nations Conference on Trade and Development (UNCTAD) in 2020 [50]. In this study, the annual average container shipping cost for the Asian-European service loop route over the recent five years (2016–2020) was taken as the shipping cost from the first year to the fifth year after refitting the LNG engine. The loss of shipping costs is because of the reduction of container space due to the LNG storage tank. Figure 3 shows the one-way (Asian-European route) shipping cost of a container vessel. The shipping space loss was multiplied by 2, as shown in Equation (9):

\[
v = 410 \text{ TEU} \times A \times 2 \times p
\]

where \(v\), \(A\) and \(p\) denote annual loss of shipping space after LNG storage tank installation (USD/year), shipping cost per container (USD/TEU), and number of voyages/year, respectively.
(3) Wage premium for crew operating LNG engines: due to the stringent safety requirements for LNG refueling, storage, and use, LNG-fueled ships are special in design, construction, and control. The crews of LNG-fueled ships are required to receive special professional training for high-pressure gas storage tanks. Therefore, the crew of LNG-fueled ships will be paid 22% more than those on regular merchant ships [51]. According to Wu’s seven years of experience as the chief officer of large merchant container vessels, the crew wages vary according to rank, route, and seniority. This variability is estimated based on the allocation of at least 16 crew members for a general merchant ship. The method to calculate the crew wage premium for a LNG-powered vessel is shown in Equation (10):

\[
w = \left(2 \text{ persons including captain and chief engineer} \times 10,000 \text{ USD/person/month} \right. \\
+ 2 \text{ persons including chief officer and second engineer} \times 6000 \text{ USD/person/month} + \\
4 \text{ persons including officers and engineers} \times 5000 \text{ USD/person/month} + \\
8 \text{ Class B crew} \times \\
3000 \text{ USD/person/month}) \times \text{wage premium rate (22%)} \times 12 \text{ months}
\]

(10)

where \(w\) represents the wage premium for crew operating LNG equipment (USD/month).

(4) Penalty for pilot fuel consumption: Vessel B uses a diesel-LNG dual fuel engine. While such engines ignite without spark plugs, they inject a small amount of fuel oil and ignite the mixture with natural gas. Therefore, there is an additional 2% (kg/kWh) cost for pilot fuel [52].

(5) Penalty for cryogenic pump fuel: LNG must be kept in a liquid state (i.e., below −162 °C) at atmospheric pressure by a cryogenic pump, which increases fuel oil consumption by 1.2% (kg/kWh) [52].

Figure 3. Shipping cost of 20-feet container freight in 2015–2020. Source: Compiled by the authors from [49].

CAPEX includes the costs of the cryogenic plant, LNG tank, total refitting of the LNG engine, operating loss due to LNG equipment installation, and crew wages during LNG equipment installation, as shown in Equation (11):

\[
s = B + C + D + E + F
\]

(11)

where \(s\), \(B\), \(C\), \(D\), \(E\), and \(F\) represent (CAPEX)\(_{LNG}\), cryogenic plant cost, LNG tank cost, total refitting cost of LNG engine, operating loss due to LNG equipment installation, and crew wages during LNG equipment installation, respectively.

The engine and installation costs of retrofitting an LNG-fueled ship are shown in Table 8. This study calculated the costs in Equation (11) according to the data in this table. The calculation methods are described as follows:
Table 8: Refit and installation costs of LNG engine.

| Item                        | Amount | Unit   |
|-----------------------------|--------|--------|
| Cryogenic plant             | 1333,800 | USD    |
| LNG tank cost               | 3510   | USD/m³ |
| Total refitting cost of LNG Engine | 405.99 | USD/kW |

Source: Compiled by the authors from Ref. [51].

1) LNG tank cost: Vessel A has been in service since it was built in 2018, and is planned to be converted into Vessel B, fueled by LNG, in this study. According to Table 5, the fuel oil tank has a capacity of 8000 m³, and the LNG storage tank has twice the capacity of the fuel oil tank [29]. Hence, a capacity of 16,000 m³ is required for the LNG storage tank. Moreover, the cost of LNG storage tank is 3510 USD/m³. The price of the LNG tank of Vessel B was calculated accordingly.

2) Total refitting cost of LNG engine: calculated by multiplying the power of the main diesel engine of Vessel A (61,800 kW) by the total refitting cost of LNG engine (405.99 USD/kW).

3) Operating loss due to LNG equipment installation: charter freight is calculated on a daily basis and varies with ship size. It takes about 90 days to refit an LNG engine and gas storage tank [53], during which time the ship shall be out of service. Based on the data of August 2021 in the Harper Petersen Index (HARPEX), which is a common international ship-chartering website, the charter freight of an 8500-TEU container vessel is 111,000 USD per day [54]. The operating loss due to the installation of LNG equipment was estimated accordingly.

4) Crew wages during LNG equipment installation: since it takes three months for refitting [53] and the crew shall be paid during this period, the crew wage is calculated by Equation (12), as follows.

\[
F = (2 \text{ persons including captain and chief engineer} \times 10,000 \text{ USD/person/month} + 2 \text{ persons including chief officer and second engineer} \times 6000 \text{ USD/person/month} + 4 \text{ persons including officers and engineers} \times 5000 \text{ USD/month} + 8 \text{ Class B crew} \times 3000 \text{ USD/person/month}) \times 3 \text{ months}
\]

where F denotes the crew wage (USD/month) during LNG equipment installation.

This study calculated the annual incremental cost of CAPEX in Equation (11) for the next five years by the sum-of-the-year’s-digits method. In this method, the net value, as obtained by subtracting the estimated net residual value from the original fixed assets, is multiplied by a fraction decreasing year by year to calculate the annual depreciation. The numerator of the fraction represents the number of years of remaining useful life of the fixed asset, and the denominator represents the sum of the years of useful life.

Vessel A is a container vessel built in 2018; the average age of container vessels around the world is 12.83 years [55]. In order to estimate the cost-benefit ratio for the next five years, this study assumed that the refitting cost of an LNG engine and gas storage tank for Vessel B would be paid off within 10 years. The annual incremental cost was calculated accordingly. Moreover, the power system of the main engine deteriorates year by year and is prone to failure; thus, its maintenance costs increase year by year. According to the researcher’s working experience in container vessels, it was estimated that the annual maintenance cost would increase by 10% each year. This implies that the factor of equipment maintenance cost is 1.1. Therefore, the maintenance cost in the second year is that of the first year multiplied by 1.1, and so on.

4.2. Calculation Method for Reduction of Pollutant Emissions

This study investigated the reduction of pollutant emissions from Vessels A and B, for which VLSFO and LNG fuels respectively were used instead of HSFO, in order to
meet the low sulfur regulations of the IMO’s MARPOL Protocol. Different pollutants may cause different effects on health and the environment. However, there is no consensus on the weights of the effects of various pollutants in environmental engineering or medical practice. Therefore, this study assumed that various pollutants are equally damaging to health and the environment. The emissions or reductions of various pollutants (including SOx, NOx, CH₄, and PM) can thus be directly added to obtain the total emissions or reductions.

The annual emissions of a pollutant from HSFO combustion can be estimated by Equation (13), as follows.

\[ G = H \times j \times i \times 10^{-6} \text{ ton/g} \]  

(13)

where \( G \), \( H \), \( j \) and \( i \) denote the annual emissions of a pollutant (tons/year), HSFO emission coefficient (g/kWh), power of the marine main engine (kW), and full-speed sailing hours (h/year), respectively.

In the above equation, the emission coefficient indicates the emissions (in g) of different pollutants from the main diesel engine per horsepower (kW) and per running hour (h), which vary with different fuels. A comparison of emission coefficients of various pollutants from burning various fuels is shown in Table 9. In order to calculate the pollutant emissions of LNG, the HSFO emission coefficient (g/kWh) in Equation (13) is changed to the LNG emission coefficient (g/kWh).

### Table 9. Comparison of emission coefficients (g/kWh) of various pollutants from burning different fuels.

| Type of Fuel       | SOx   | NOx   | CO₂   | CH₄   | PM    |
|-------------------|-------|-------|-------|-------|-------|
| HSFO (containing 2.5 wt.% S) | 10.29 | 14.40 | 607   | 0.010 | 1.42  |
| VLSFO (containing 0.5 wt.% S) | 0.51  | 13.54 | 533   | 0.005 | 0.20  |
| LNG               | 0.14  | 3.40  | 417   | 0.13  | 0.10  |

Source: Compiled by the authors from [56].

In Equation (13), the full-speed sailing hours are 5660 h/year, and the power of the marine main engine is 61,800 kW. Pollutant emissions from the ships are reduced after Strategies VLSFO and LNG are applied. The annual emission reduction of a pollutant (tons/year) when HSFO is replaced with VLSFO can be calculated by Equation (14):

\[ I = J - [K \times j \times i \times 10^{-6} \text{ ton/g}] \]  

(14)

where \( I \), \( J \), \( K \), \( j \) and \( i \) denote the emission reduction of a pollutant (tons/year), annual emissions of a pollutant after HSFO is used (tons/year), VLSFO emission coefficient (g/kWh), power of the marine main engine (kW), and full-speed sailing hours (h/year), respectively.

In the above equation, the annual emissions of a pollutant after HSFO is used (tons/year) were calculated by Equation (13). In order to calculate the pollutant emission reduction of LNG, the VLSFO emission coefficient (g/kWh) in Equation (14) was changed to the LNG emission coefficient (g/kWh).

Equations (15) and (16) were used to calculate the total pollutant emission reductions and rates of total pollutant emission reduction for different fuels over the next five years, respectively, as shown below:

\[ L = M - N \]  

(15)

\[ Q = \frac{L}{M} \times 100\% \]  

(16)

where \( L \), \( M \), \( N \) represent the total pollutant emission reduction within five years, total pollutant emission over five years after using HSFO, and the total pollutant emission over five years after replacing with VLSFO or LNG, respectively.

The aftertreatment systems of the engines fuelled with HSFO, VLSFO or LNG are installed at the exhaust gas pipe in order to catalyze or remove certain compounds from
exhaust emissions. However, both engine performance and aftertreatment system characteristics deteriorate over time. Hence, the combustion characteristics of the engines and catalytic performance of the aftertreatment system would decrease year by year, leading to a gradual increase in the emissions coefficients of various pollutants over the usage period from the first year of the implementation of the given strategy. As the deterioration rates of various pollutants are different, when estimating the pollutant emissions for the next five years, it is necessary to consider the gradually increased emission coefficients year by year. The emission deterioration factors of pollutants from ships in this study refer to data from Port California [57], as shown in Table 10, in order to calculate the emissions of various pollutants for the next five years, as shown in Equation (17).

\[
P = R \times S \times j \times i \times 1 \times 10^{-6} \text{tons/g} \tag{17}
\]

where \(P\), \(R\), \(S\), \(j\), and \(i\) represent the annual pollutant emission (tons/year), engine deterioration factor, emission coefficient (g/kWh), the output power of the marine main engine (kW), and full-speed sailing hours (h/year), respectively.

### Table 10. Deterioration factors of various emissions from the marine engine. Unit: %/year.

|        | SOx   | NOx   | CH\(_4\) | PM    | CO\(_2\) |
|--------|-------|-------|----------|-------|----------|
| Data   | 1.023 | 1.021 | 1.044    | 1.067 | 1.025    |

Source: Compiled by the authors from [57].

#### 4.3. Cost-Benefit Analysis Methodology

Cost-benefit analysis (CBA) is a method to evaluate the ratios of the incremental costs to the benefits obtained from implementing various strategies. The purpose of this method is to seek a way to obtain the maximum benefit at the minimum cost. This study conducted a cost-benefit analysis to determine the optimal strategy based on cost-benefit ratios (CBR).

The benefit defined in this study is the total pollutant emission reduction (tons/year) after fuel change from HSFO to either VLSFO or LNG. Equation (18) was used to calculate the cost-benefit ratio (CBR) of a strategy, as follows:

\[
T = \frac{L}{Y} \tag{18}
\]

where \(T\), \(L\), and \(Y\) represent the CBR (cost-benefit ratio), total pollutant emission reduction (tons), and total incremental cost required (kUSD), respectively.

A strategy with a high CBR indicates that it is highly cost-effective. This implies that the total pollutant emission reduction of this fuel is greater at the same total incremental cost, and thus, that it is a suitable strategy for rapid adoption.

#### 5. Results and Discussion

##### 5.1. Comparison of Total Incremental Costs of Different Strategies

The total incremental cost of the VLSFO strategy was calculated by Equation (1). Among the costs, the environmental fuel fee (EFF) is an additional fee charged by shipping lines given the high cost of VLSFO. FEE is negative and is calculated by Equation (5). The incremental costs from the first to the fifth year are calculated and shown in Table 11.
According to Table 11, the total incremental cost of the VLSFO strategy in five years is 16,412 kUSD. If HSFO continues to be used without any change, the total annual fuel cost can be calculated by Equation (3). The total fuel cost of HSFO from the first to the fifth year is 126,791 kUSD. This implies that the cost expenditure of the VLSFO strategy increases by 12.94% over five years in comparison with that of HSFO.

The total incremental cost of the LNG strategy was calculated by Equation (6). As this study explored the cost of different fuels for the next five years, the annual (CAPEX) LNG was amortized and calculated by the sum-of-the-years’-digits method [58].

The loss of shipping space due to installation of LNG storage tank was calculated by Equation (9). For Vessel B adopting the LNG strategy, the LNG storage tank occupies a shipping space of 410 TEU, and the average freight (USD/TEU) of each shipping space is based on the data shown in Figure 3. In addition, Vessel B makes five voyages a year, with each lasting about 76 days, and the annual loss of shipping space is calculated on this basis.

There are six other items in OPEX for the LNG strategy, including the price difference between LNG and HSFO and the LNG equipment maintenance cost. The annual total incremental costs of the LNG strategy were calculated and are shown in Table 12.

Table 12 shows that other OPEXs for the LNG strategy includes LNG equipment maintenance costs, loss of shipping space due to LNG equipment installation, and the wage premium for crew operating LNG equipment. As LNG is a clean fuel, the main marine engine maintenance cost is relatively low. In comparison with HSFO, the maintenance tasks, such as removing carbon residue and oily sludge and maintaining heating pipes, can be reduced. Therefore, the maintenance costs for an engine fueled by LNG are lower than those of one fueled by HSFO. According to Table 12, the refitting cost of an LNG engine and the installation of an LNG storage tank cost account for the largest proportion in the incremental costs of Vessel B. However, the LNG equipment cost decreases year by year.
as it ages. Additionally, the fuel price difference between LNG and HSFO is significant. Therefore, the total incremental cost of Vessel B adopting the LNG strategy decreases significantly after the first year. It is estimated that the total incremental cost of the LNG strategy will be 28,018 kUSD over the next five years.

The annual total incremental cost was calculated by adding up the incremental costs of all items each year, as shown in Figure 4. After installation, the total incremental cost of the VLSFO strategy decreased gradually from 3596 kUSD in the first year to 2994 kUSD in the fifth year, mainly because the fuel price difference between the HSFO and VLSFO is predicted to be stable over the next five years. When the IMO convention for low sulfur fuel was implemented in 2020, the premium between VLSFO and HSFO surpassed 250 tons/USD. However, the situation is different now. While the price of VLSFO is still higher than that of HSFO, it fluctuates with the prices of HSFO and international crude oil. In addition, the cost of lubricant additives is decreasing year by year due to the evolution of manufacturing techniques. Thus, the annual incremental cost of the VLSFO strategy will continue to decrease year by year over the next five years. As such, if the VLSFO strategy is adopted, the main risk for shipping lines will be uncertainty regarding the price of VLSFO fuel. However, as the environmental fuel fee (EFF) fluctuates with fuel prices [59], some risks arising from oil price fluctuations shall be shared among shipping lines and shippers.

The LNG strategy is adopted by Vessel B, and after installation of the LNG engine, the annual incremental cost of Vessel B will drop rapidly from 8516k USD in the first year to 2658k USD in the fifth year, due to the large initial investment of the refitting process. However, the fuel price of LNG is estimated to be lower than that of HSFO in the next five years, and the difference will likely grow over time. Therefore, after the LNG strategy is adopted, the annual incremental cost falls as (CAPEX)_{LNG} decreases year by year. It is worth noting that the main risk associated with the LNG strategy is the large investment in the initial refitting of the LNG engine and gas storage tank.

Furthermore, the total incremental cost over a five-year period after the adoption of the LNG strategy is 28,108 kUSD, which indicates a 22.16% increase in five years, as compared with the total HSFO cost of 126,791 kUSD without any strategy. In addition, Figure 4 shows that the total incremental cost of the LNG strategy is much higher than that of the VLSFO strategy, although this gap decreases year by year. After 4.7 years, the total incremental cost of the LNG strategy matches that of the VLSFO strategy. After that, the trend of the two curves in Figure 4 is reversed, meaning the total incremental cost of the VLSFO strategy is higher than that of the LNG strategy, and the gap between their total incremental costs continues to widen after 4.7 years.

In the next five years, the total incremental cost of the LNG strategy is 28,108 kUSD, which is 9.22% higher than that of the VLSFO strategy at 16,412 kUSD. This implies that

![Figure 4. Total incremental costs of the VLSFO and LNG strategies over a five-year period.](image-url)
the total incremental cost of the LNG strategy in the next five years is significantly higher than that of the latter. While the fuel price of LNG is cheaper than VLSFO, the refitting of an LNG engine and the installation of a gas storage tank is expensive. Hence, the initial refitting cost of an LNG engine is a key factor in determining the total incremental costs of the two strategies over the next five years.

5.2. Comparison of Pollutant Emission Reductions of Different Strategies

Pollutant emission reductions by different strategies are important data for cost-benefit evaluations. The pollutant emission reductions of the VLSFO strategy were calculated by Equation (14). The ship discussed in this article uses a marine main engine with a nominal power of 61,800 kW, and sails at full speed for 5660 h/year. The results of our calculated emission reductions in the first year after the VLSFO strategy is adopted are shown in Table 13.

Table 13. Pollutant emission reductions of the VLSFO strategy in the first year.

| Pollutant | HSFO Emission Coefficient (g/kWh) | VLSFO Emission Coefficient (g/kWh) | HSFO Emission (Tons) | VLSFO Emission (Tons) | Pollutant Emission Reduction (Tons) | Total Pollutant Emission Reduction (Tons) |
|-----------|----------------------------------|-------------------------------------|----------------------|-----------------------|------------------------------------|----------------------------------------|
| SOx       | 10.29                            | 0.51                                | 3599                 | 178                   | 3421                               | 4150                                   |
| NOx       | 14.4                             | 13.54                               | 5037                 | 4736                  | 301                                |                                        |
| CH₄       | 0.01                             | 0.005                               | 3                    | 2                     | 1                                  |                                        |
| PM        | 1.42                             | 0.2                                 | 497                  | 70                    | 427                                |                                        |

According to Table 13, after HSFO fuel is changed to VLSFO, SOx, NOx, CH₄, and PM emissions are reduced by 3421 tons, 301 tons, 1 ton, and 427 tons, respectively, in the first year, i.e., emission reduction rates of 95%, 6.0%, 50.0%, and 85.9%, respectively. Therefore, the VLSFO strategy is effective for reducing SOx and PM emissions, which is consistent with the study results of Krakowski [60].

The calculation results of pollutant emission reductions for Vessel B after adopting the LNG strategy, determined by Equation (14), in the first year are shown in Table 14.

Table 14. Pollutant emission reductions of the LNG strategy in the first year.

| Pollutant | HSFO Emission Coefficient (g/kWh) | LNG Emission Coefficient (g/kWh) | HSFO Emission (Tons) | LNG Emission (Tons) | Pollutant Emission Reduction (Tons) | Total Pollutant Emission Reduction (Tons) |
|-----------|----------------------------------|----------------------------------|----------------------|---------------------|------------------------------------|----------------------------------------|
| SOx       | 10.29                            | 0.14                             | 3599                 | 49                  | 3550                               | 7818                                   |
| NOx       | 14.4                             | 3.4                              | 5037                 | 1189                | 3848                               |                                        |
| CH₄       | 0.01                             | 0.13                             | 3                    | 45                  | –42                                |                                        |
| PM        | 1.42                             | 0.1                              | 497                  | 35                  | 462                                |                                        |

According to Table 14, the LNG strategy significantly reduces SOx, NOx, and PM emissions by 3550 tons, 3848 tons, and 462 tons, respectively, in the first year, i.e., reductions of 98.6%, 76.4%, and 93.0%, respectively. However, it is worth noting that the LNG strategy increases CH₄ emissions by 42 tons. This is due to the fact that LNG is liquefied at low temperature (−162 °C), and incomplete combustion or leakage can occur, leading to increased CH₄ emissions. Methane (CH₄) is also a significant source of greenhouse gas. Its 100-year global warming potential is about 28–34 times that of CO₂. The amount of CH₄ emission is only 45 tons, in comparison with 66,460 tons of CO₂ from the same engine in the first year after implementing the LNG strategy. Herdzik [61] found that that the problem of methane leakage is nearly eliminated in modern LNG engines. Hence, in this study, CH₄ was included with other pollutants such as SOx and NOx in Table 14.
Since the performance of aftertreatment systems for the exhaust gases of marine diesel engines deteriorates year by year, the emission coefficients of various pollutants increase over time. Thus, the effects of emission reduction decrease year by year. As the quantities of various pollutants increase at different rates, the annual pollutant emission coefficients due to the deterioration of the aftertreatment system must be estimated first when estimating pollutant emissions amounts. Therefore, the emissions reductions of various pollutants in the VLSFO and LNG scenarios decrease over time, as shown in Table 15:

Table 15. Total pollutant emission reductions of the VLSFO and LNG strategies over a five-year period. Unit: tons.

| Strategy | Implementation Time |
|----------|---------------------|
|          | 1st Year | 2nd Year | 3rd Year | 4th Year | 5th Year |
| VLSFO    | 4150      | 4264     | 4381     | 4503     | 4629     |
| LNG      | 7818      | 8009     | 8206     | 8409     | 8664     |

A comparison of Tables 13 and 14 in the first year after replacing HSFO with VLSFO or LNG shows that the total pollutant emission reduction of the LNG strategy is 3668 tons more than that of the VLSFO strategy. Furthermore, according to Table 15, the total pollutant emission reduction of the LNG strategy in the fifth year is 4035 tons more than that of the VLSFO strategy. With the total pollutant emissions of HSFO in five years as the reference value, the total pollutant emission reduction of the LNG strategy is significantly higher than that of the VLSFO strategy, i.e., 86% and 46% of the reference value, respectively. In consequence, the LNG strategy may be an environmentally friendly and sustainable option for fleets seeking to adopt the IMO low sulfur policy.

Carbon dioxide (CO$_2$) is a colorless, odorless gas formed mainly through the complete combustion reaction of hydrocarbon fuels. As it is a significant greenhouse gas, this study estimates the amounts of CO$_2$ reduction by the adoption of the VLSFO and LNG strategies. According to Table 16, compared with the total CO$_2$ emission from burning HSFO, the total CO$_2$ emissions from burning LNG and VLSFO over five years of use are reduced by 25.7% and 10.0%, respectively. This indicates that the LNG strategy is 15.7% more effective in terms of CO$_2$ emission reductions than the VLSFO strategy.

Table 16. Annual CO$_2$ emission reductions by the VLSFO and LNG strategies. Unit: tons.

| Strategy | Implementation Time |
|----------|---------------------|
|          | 1st Year | 2nd Year | 3rd Year | 4th Year | 5th Year |
| VLSFO    | 25,884    | 26,531   | 27,195   | 27,875   | 28,571   |
| LNG      | 66,460    | 68,121   | 69,824   | 71,570   | 73,359   |

Changes in the total emissions of pollutants, such as SOx and PM, total pollutant emission reduction, and emission reduction rates over a five-year period due to the adoption of the VLSFO and LNG strategies were calculated by Equations (13)–(17), as shown in Table 17.

According to Table 17, the VLSFO strategy can effectively reduce SOx, NOx, CH$_4$, and PM emissions by 95.0%, 5.9%, 50%, and 85.9% in five years, respectively, while the LNG strategy can effectively reduce SOx, NOx, and PM emissions by 98.6%, 76.3%, and 92.9%, respectively. Therefore, the LNG strategy is more effective at reducing SOx, NOx and PM emissions than the VLSFO strategy. However, increased CH$_4$ emissions occur with the LNG strategy.
Table 17. Total pollutant emission reduction (in tons) and total pollutant emission reduction rates (in %) with the adoption of the VLSFO and LNG strategies over a five-year period.

| Pollutants | Total Emission in Five Years | Total Pollutant Emission Reduction in Five Years | Total Pollutant Emission Reduction Rate in Five Years (%) |
|------------|-----------------------------|-----------------------------------------------|--------------------------------------------------------|
| SOx        | HSFO 18,844                  | –                                             | –                                                      |
|            | VLSFO 934                   | 17,910                                        | 95.0                                                   |
|            | LNG 256                     | 18,587                                        | 98.6                                                   |
| NO\(_x\)   | HSFO 21,228                  | –                                             | –                                                      |
|            | VLSFO 19,960                | 1268                                          | 5.9                                                    |
|            | LNG 5012                    | 16,216                                        | 76.3                                                   |
| CH\(_4\)   | HSFO 16                     | –                                             | –                                                      |
|            | VLSFO 8                     | 8                                             | 50.0                                                   |
|            | LNG 203                     | −187                                          | −1168                                                  |
| PM         | HSFO 2839                   | –                                             | –                                                      |
|            | VLSFO 399                   | 2439                                          | 85.9                                                   |
|            | LNG 200                     | 2639                                          | 92.9                                                   |

As shown in Tables 11 and 12, the total incremental costs of the VLSFO and LNG strategies increase by 12.94% and 22.16%, respectively, compared with ships with no measures taken during the same five-year period. This indicates that extra costs will be incurred no matter which clean fuel is chosen [62]. However, the total incremental cost of the LNG strategy over five years is 9.22% higher than that of the VLSFO strategy. However, the results in Table 17 show that LNG is much more effective in reducing emissions of various pollutants, except CH\(_4\).

5.3. Comparison of Cost-Benefit Ratios

The cost-benefit ratio (CBR) refers to ratio of the incremental cost to the benefit of pollutant emission reduction, as defined in Equation (18). A high cost-benefit ratio indicates that a strategy is more advantageous.

In the first year after replacing different fuels, while the CBR of the VLSFO strategy is higher than that of the LNG strategy, the gap between the two gradually narrows. As the refitting costs of an LNG engine decrease, the CBR of the LNG strategy approaches that of the VLSFO strategy at 2.5 years (see Figure 5). After that, the curve trend is reversed, meaning that the CBR of the LNG strategy is higher than that of the VLSFO strategy, and the gap between the two CBRs widens year by year. In the fifth year, the CBR gap between the two strategies reaches 1.71, as shown in Figure 5.
Regarding the cost-benefit ratio, that of the VLSFO strategy is higher in the first 2.5 years, which indicates that emissions are more effectively reduced at the same total incremental cost. Therefore, the VLSFO strategy is advantageous in the first 2.5 years after its adoption. In contrast, later, the cost-benefit ratio of the LNG strategy is higher than that of the former, presumably because of the decrease of LNG price. Moreover, the large initial investment in LNG equipment is amortized year by year, which results in a decline in the total incremental cost and a rapid rise in the cost-benefit ratio. Therefore, this study concludes that LNG is a suitable substitute for HSFO as a marine fuel as a long-term strategy, while the VLSFO strategy is suitable as a short-term solution.

6. Conclusions

This study evaluated the strategies which shipping lines could potentially adopt to meet the low sulfur policy of MARPOL by SWOT and cost-benefit analyses. Significant results may be summarized as follows.

1. After a feasibility evaluation, installing scrubbers on the exhaust gas systems of a vessel was found to be only a transitional plan from the perspective of environmental protection and sustainable operation.

2. The compression-ignition diesel-LNG dual-fuel engine was found to be more fuel flexible. Dual-fuel engines can maintain existing engine architectures which are suitable for engine refitting. Moreover, STS (Ship-to-Ship) and PTS (Port-to-Ship) LNG refueling methods are more suitable for large ocean-going merchant ships.

3. The total incremental cost of the LNG strategy was found to be higher than that of the VLSFO strategy in the first 4.7 years; however, over longer periods, the curve trends reversed, make the VLSFO strategy more costly than the LNG strategy.

4. The total incremental cost of the LNG strategy in five years is 9.22% higher than that of the VLSFO strategy.

5. The LNG strategy more effectively reduces SOx, NOx, and PM emissions but produces more CH4 emission than the VLSFO strategy. The total pollutant emission reduction of the LNG strategy in five years is much higher than that of the VLSFO strategy. In addition, due to the gradual deterioration in the performance of the aftertreatment system for exhaust gases, the pollutant emission reductions of both strategies show a decreasing trend year by year.

6. The CO2 emission reduction rate of the LNG strategy is much higher than that of the VLSFO strategy, i.e., by 15.7%. the LNG strategy is very effective in reducing CO2 emissions.

7. The cost-benefit ratio of the LNG strategy is higher than that of the VLSFO strategy 2.5 years after implementation, and the gap of the cost-benefit ratios between the two strategies widens year by year. the LNG strategy is considered an adequate medium- and long-term strategy for shipping lines to respect the low sulfur policy of the IMO, while the VLSFO strategy is a suitable short-term strategy.

Author Contributions: Conceptualization, C.-Y.L.; funding acquisition, C.-Y.L.; methodology, C.-Y.L.; draft preparation, P.-C.W.; formal analysis, C.-Y.L.; corresponding, C.-Y.L.; investigation, P.-C.W.; writing and editing, C.-Y.L.; supervision, C.-Y.L.; validation, P.-C.W. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by Ministry of Science and Technology of Taiwan, ROC, under contract No. MOST 107-2221-E-019-056-MY2 and MOST 105-2221-E-019-066.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study are contained within this article.
Acknowledgments: The authors gratefully acknowledge the financial support from Ministry of Science and Technology of Taiwan, ROC, under contract No. MOST 107-2221-E-019-056-MY2 and MOST 109-2221-E-019-024.

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

Nomenclatures

| Abbreviation | Full Name                                      |
|--------------|------------------------------------------------|
| AHP          | analytic hierarchy process                    |
| CAPEX        | Capital Expenditure                           |
| CBA          | Cost-Benefit analysis                         |
| CBR          | Cost-Benefit Ratio                            |
| EFF          | Environmental fuel fee                         |
| FEU          | Forty-Foot Equivalent Unit                    |
| HSFO         | High Sulfur Fuel Oil                          |
| IMO          | International Maritime Organization            |
| kUSD         | Thousand United States Dollar                 |
| LNG          | Liquefied natural gas                         |
| MARPOL       | International Convention for the Prevention of Pollution from Ships |
| PM           | Particulate Matter                            |
| PTS          | Port-to-ship                                  |
| SECA         | Sulfur Emission Control Area                  |
| STS          | ship-to-ship                                  |
| SWOT         | Strength-Weakness-Opportunity-Threat          |
| TEU          | Twenty-Foot Equivalent Unit                   |
| TTS          | truck-to-ship                                 |
| UNCATD       | United Nations Conference on Trade and Development |
| VLSFO        | Very Low Sulfur Fuel Oil                      |

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