With technological advancements and the rise of global trade, the shipping industry plays an increasingly important role in international cargo transportation. However, its rapid growth has also caused serious environmental problems. According to the International Maritime Organization (IMO), shipping emissions accounted for 2.89% of global human-caused emissions in 2018, because of an increase in shipping activities, the number of ships, and their size.

Additionally, ships often stay in ports for several hours or even days, using their engines to unload and upload cargo and operate port activities. This process releases a large amount of sulfur oxides (SOX) and nitrogen oxides (NOX), which are considered major contributors to seawater acidification. IMO predicts that if no emission control measures are taken, ship emissions in 2050 could be twice as high as in 2007. Therefore, to reduce pollution from ships, IMO and governments worldwide have introduced various energy-saving and emission-reduction measures.

An Emission Control Area (ECA) is a designated sea area where stricter regulations are enforced to reduce air pollution from ships. Initially, these rules targeted SOX, but in 2005, they were expanded to include NOX in some areas. While SOX-only ECAs are called SECAs (Sulfur Emission Control Areas), NOX-restricted ECAs are known as NECAs (Nitrogen Emission Control Areas).

Since January 1, 2015, the maximum sulfur content in marine fuel must not exceed 0.1% (1000 ppm). Existing SECA zones include the Baltic Sea, North Sea, and North American coastal waters, covering both U.S. and Canadian coastlines, as well as the U.S. Caribbean Sea. The Mediterranean Sea will be added to SECA in 2025. For NOx emissions, MARPOL Annex VI sets three-tiered standards (Tier 1, Tier 2, and Tier 3), based on ship construction year and navigation area. Tier 3 applies only to newly built ships operating in NECA zones, which currently include the North Sea, Baltic Sea, and U.S. coastal waters.

1. Scrubber

One way to reduce emissions and comply with ECA regulations is to install scrubber technology. Scrubbers allow ships to continue using traditional heavy fuel oil (HFO) within ECAs, avoiding the extra cost of switching to low-sulfur fuel (MGO). In a scrubber system, before ship exhaust gases are released into the air, SOx are removed by being sprayed with liquid. Scrubbers can remove up to 95% of SOx, reduce particulate matter (PM) emissions, and meet IMO sulfur emission limits. However, installing scrubbers may also increase fuel and power consumption.

To analyze its impact on vessel costs, the installation of scrubber is used as a substitute in the calculation. The result of chain cost calculation can be seen in Table X. It shows that the marine time cost decreased 0.8% after the installation of scrubber, while other related costs did not change; therefore, total generalised chain cost decreased 0.2%.

According to the calculation model, the only vessel cost component affected by the scrubber installation is fuel cost ship ECA as stated in Table X. It refers to the expenses incurred when buying fuel that complies with ECA regulations for ships operating in SECA or NECA zones. The fuel cost ship ECA decreases by 33.3%, from €19.76 to €13.18 /TEU, because of scrubber installation, because vessels equipped with scrubbers can continue using HFO instead of MGO, which costs €325 per tonne more than HFO. Although scrubber operation increases power and fuel consumption, the additional cost is generally lower than the price difference between HFO and MGO. As a result, the overall fuel cost ship ECA decreases.

Comparison of Chain Cost: With vs Without LNG for Xiamen – Zeebrugge route

|  |  |  |  |
| --- | --- | --- | --- |
| Chain Cost Components | Regular Fuel | Scrubber only | Change |
| From Hinterland cost | 1085.74820 | 1085.74820 | 0 |
| From Port cost | 99.65251 | 99.65251 | 0 |
| Maritime cost | 637.59082 | 632.24188 | -0.00839 |
| To Port cost | 381.82987 | 381.82987 | 0 |
| To Hinterland cost | 390.61684 | 390.61684 | 0 |
| Total generalised chain cost | 2595.43824 | 2590.08931 | -0.00206 |

Comparison of Vessel Cost: With vs Without Scrubber

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Vessel Cost Component | Regular Fuel | | Scrubber only | | Change |
| Total cost  per leg | Cost/ TEU | Total cost  per leg | Cost/ TEU |  |
| Running cost ship | 480936.36 | 20.069 | 480936.36 | 20.069 | 0 |
| Manning cost ship | 207612.09 | 8.663 | 207612.09 | 8.663 | 0 |
| Store cost | 8306.57 | 0.347 | 8306.57 | 0.347 | 0 |
| Insurance cost | 217422.36 | 9.073 | 217422.36 | 9.073 | 0 |
| Repair and Maintainance cost | 18890.76 | 0.788 | 18890.76 | 0.788 | 0 |
| Management cost | 28704.57 | 1.198 | 28704.57 | 1.198 | 0 |
| Voyage cost ship | 7626546.21 | 318.250 | 7468903.58 | 311.672 | -0.021 |
| Fuel cost ship in Port | 202937.41 | 8.468 | 202937.41 | 8.468 | 0 |
| Fuel cost ship ECA | 473412.93 | 19.755 | 315770.3 | 13.177 | -0.333 |
| Fuel cost ship Non ECA | 4454960.32 | 185.902 | 4454960.32 | 185.902 | 0 |
| Lub oil cost ship | 27717.86 | 1.157 | 27717.86 | 1.157 | 0 |
| Cannel cost ship | 2053900.37 | 85.708 | 2053900.37 | 85.708 | 0 |
| ETS cost ship | 413617.32 | 17.260 | 413617.32 | 17.260 | 0 |
| External cost at sea | . |  | . |  |  |
| Port cost |  |  |  |  |  |
| Total port charges | 1302973.74 | 54.372 | 1302973.74 | 54.372 | 0 |
| Port handling cost | 7403357.85 | 308.937 | 7403357.85 | 308.937 | 0 |
| Total variable cost ship per loop  (including port charges) | 9410456.3 | 392.691 | 9252813.67 | 386.113 | -0.017 |
| Fixed cost ship per loop | 3977508.98 | 165.979 | 3977508.98 | 165.979 | 0 |
| Total port handling cost per loop | 7403357.85 | 308.937 | 7403357.85 | 308.937 | 0 |
| Total cost ship per loop | **20791323.13** | **867.607** | **20633680.5** | **861.028** | -0.008 |

1. LNG

LNG (Liquefied Natural Gas) is considered an alternative fuel for shipping, because it has very low sulfur content and produces less NOx, PM, and CO₂ compared to traditional fuels. This helps reduce pollution and lower the environmental impact of shipping. Additionally, in some markets, LNG is more cost-competitive than MGO and HFO. However, since LNG bunkering facilities are limited, refueling can be inconvenient, thus reducing operational flexibility for shipping companies.

To analyze its impact on vessel costs, LNG fuel is used as a substitute in the calculation. The result of chain cost calculation can be seen in Table X. As shown in the table, LNG significantly increases maritime costs by up to 85%, leading to a total generalized chain cost of 3138, which is 1.2 times higher than using MDO.

Furthermore, according to the calculation model, LNG fuel has a substantial impact on vessel costs, particularly voyage costs, which now account for 84% to 94% of the total variable cost per loop. As shown in Table X, the fuel cost in ECA zones increased by 265%, while in Non-ECA zones, it rose by 447%, and in ports, it increased by 7%. This indicates that the primary cost increase comes from fuel expenses, as LNG (3564 EUR/ tonne) is significantly more expensive than HFO(651 EUR/ tonne) and MDO (976 EUR/ tonne), leading to a sharp rise in overall costs.

Comparison of Chain Cost: With vs Without LNG Directive for Xiamen – Zeebrugge route

|  |  |  |  |
| --- | --- | --- | --- |
| Chain Cost Components | Regular Fuel | Scrubber or LNG | Change |
| From Hinterland cost | 1085.74820 | 1085.74820 | 0 |
| From Port cost | 99.65251 | 99.65251 | 0 |
| Maritime cost | 637.59082 | 1180.09232 | 0.850861532 |
| To Port cost | 381.82987 | 381.86849 | 0.000101135 |
| To Hinterland cost | 390.61684 | 390.61684 | 0 |
| Total generalised chain cost | 2595.43824 | 3137.97837 | 0.209036038 |

Comparison of Vessel Cost: With vs Without LNG

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Vessel Cost Component | Regular Fuel | | Scrubber or LNG | | Change |
| Total cost  per leg | Cost/ TEU | Total cost  per leg | Cost/ TEU |  |
| Running cost ship | 480936.36 | 20.069 | 480936.36 | 20.069 | 0 |
| Manning cost ship | 207612.09 | 8.663 | 207612.09 | 8.663 | 0 |
| Store cost | 8306.57 | 0.347 | 8306.57 | 0.347 | 0 |
| Insurance cost | 217422.36 | 9.073 | 217422.36 | 9.073 | 0 |
| Repair and Maintainance cost | 18890.76 | 0.788 | 18890.76 | 0.788 | 0 |
| Management cost | 28704.57 | 1.198 | 28704.57 | 1.198 | 0 |
| Voyage cost ship | 7626546.21 | 318.250 | 28830499.3 | 1203.075 | 2.781 |
| Fuel cost ship in Port | 202937.41 | 8.468 | 217162.47 | 9.062 | 0.070 |
| Fuel cost ship ECA | 473412.93 | 19.755 | 1728733.28 | 72.139 | 2.652 |
| Fuel cost ship Non ECA | 4454960.32 | 185.902 | 24389368. | 1017.750 | 4.475 |
| Lub oil cost ship | 27717.86 | 1.157 | 27717.86 | 1.157 | 0 |
| Cannel cost ship | 2053900.37 | 85.708 | 2053900.37 | 85.708 | 0 |
| ETS cost ship | 413617.32 | 17.260 | 413617.32 | 17.260 | 0 |
| External cost at sea | . |  | . |  |  |
| Port cost |  |  |  |  |  |
| Total port charges | 1302973.74 | 54.372 | 1302973.74 | 54.372 | 0 |
| Port handling cost | 7403357.85 | 308.937 | 7403357.85 | 308.937 | 0 |
| Total variable cost ship per loop  (including port charges) | 9410456.3 | 392.691 | 30614409.4 | 1277.517 | 2.253 |
| Fixed cost ship per loop | 3977508.98 | 165.979 | 3977508.98 | 165.979 | 0 |
| Total port handling cost per loop | 7403357.85 | 308.937 | 7403357.85 | 308.937 | 0 |
| Total cost ship per loop | **20791323.13** | **867.607** | **41995276.22** | 1752.432 | 1.020 |

FuelEU Maritime establishes maximum limits on the annual average greenhouse gas (GHG) intensity of energy used by ships, which exceed 5,000 gross tonnage that call at European ports, regardless of their flag. The regulation aims to ensure a gradual reduction in the GHG intensity of fuels used in the maritime sector, and the target of FuelEU starts with a 2% decrease by 2025 and reaches an 80% reduction by 2050. In the model, FuelEU Maritime is considered within the framework of the Emissions Trading System (ETS), as its impact on fuel choices and emissions indirectly influences ETS-related costs. In the model, ETS costs are set to zero when FuelEU Maritime is not applied because, in this scenario, ships are not required to comply with the EU Emissions Trading System (ETS). In other words, without FuelEU, there is no obligation to purchase carbon allowances (EUAs), and vessels can continue using conventional fuels without incurring ETS-related expenses.

The chain cost calculation, presented in Table X, shows that FuelEU implementation impacts maritime and port-related costs. Specifically, if FuelEU is not implemented, maritime costs decrease by 0.4%, and to-port costs decrease by 0.3%. This cost reduction may be due to ships using cheaper fuels and the absence of additional administrative costs in ports related to FuelEU compliance. Overall, the total generalized cost decreases by 0.1%.

The implementation of FuelEU directives mainly affects the ETS cost of ships in the calculation model, as shown in Table X. The results indicate that the total annual ship cost decreases by 2% if FuelEU is not implemented. To reduce ETS cost of ship, the shippers can choose shorter to reduce fuel consumption and emissions. Avoiding congested areas where ships may have to slow down or idle, can also decrease fuel use, this leading to a decrease in ETS cost of ship. Additionally, planning ship arrivals efficiently can also reduce waiting time at ports, thus avoiding unnecessary fuel use and cutting ETS costs.

Comparison of Chain Cost: With vs Without FuelEU Directive for Xiamen – Zeebrugge route

|  |  |  |  |
| --- | --- | --- | --- |
| Chain Cost Components | Regular Fuel | No FuelEU | Change |
| From Hinterland cost | 1085.74820 | 1085.74820 | 0.000 |
| From Port cost | 99.65251 | 99.65251 | 0.000 |
| Maritime cost | 637.59082 | 635.13984 | -0.004 |
| To Port cost | 381.82987 | 380.72794 | -0.003 |
| To Hinterland cost | 390.61684 | 390.61684 | 0.000 |
| Total generalised chain cost | 2595.43824 | 2591.88534 | -0.001 |

Comparison of Vessel Cost: With vs Without LNG

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Vessel Cost Component | Regular Fuel | | No FuelEU | | Change |
| **Total cost**  **per leg** | **Cost/ TEU** | **Total cost**  **per leg** | **Cost/ TEU** |  |
| Running cost ship | 480936.36 | 20.069 | 480936.36 | 20.069 | 0 |
| Manning cost ship | 207612.09 | 8.663 | 207612.09 | 8.663 | 0 |
| Store cost | 8306.57 | 0.347 | 8306.57 | 0.347 | 0 |
| Insurance cost | 217422.36 | 9.073 | 217422.36 | 9.073 | 0 |
| Repair and Maintainance cost | 18890.76 | 0.788 | 18890.76 | 0.788 | 0 |
| Management cost | 28704.57 | 1.198 | 28704.57 | 1.198 | 0 |
| Voyage cost ship | 7626546.21 | 318.250 | 7212928.89 | 300.990 | -0.054 |
| Fuel cost ship in Port | 202937.41 | 8.468 | 202937.41 | 8.468 | 0.070 |
| Fuel cost ship ECA | 473412.93 | 19.755 | 473412.93 | 19.755 | 2.652 |
| Fuel cost ship Non ECA | 4454960.32 | 185.902 | 4454960.32 | 185.902 | 4.475 |
| Lub oil cost ship | 27717.86 | 1.157 | 27717.86 | 1.157 | 0 |
| Cannel cost ship | 2053900.37 | 85.708 | 2053900.37 | 85.708 | 0 |
| ETS cost ship | 413617.32 | 17.260 | . | . | 0 |
| External cost at sea | . |  | . |  |  |
| Port cost |  |  |  |  |  |
| Total port charges | 1302973.74 | 54.372 | 1302973.74 | 54.372 | 0 |
| Port handling cost | 7403357.85 | 308.937 | 7403357.85 | 308.937 | 0 |
| Total variable cost ship per loop  (including port charges) | 9410456.3 | 392.691 | 8996838.98 | 392.691 | 0 |
| Fixed cost ship per loop | 3977508.98 | 165.979 | 3977508.98 | 165.979 | 0 |
| Total port handling cost per loop | 7403357.85 | 308.937 | 7403357.85 | 308.937 | 0 |
| Total cost ship per loop | **20791323.13** | **867.607** | **20377705.81** | **850.347** | -0.020 |