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Voyage-Based Emission Profiles and the Impact of LNG as a Marine Fuel in the Environmental Performance of Container Ships Operating on the Same Line Route

Sefer Bazlı Emisyon Profilleri ve Deniz Yakıtı Olarak LNG'nin Aynı Hat Rotasında Çalışan Konteyner Gemilerinin Çevresel Performansına Etkisi

Türk Denizcilik ve Deniz Bilimleri Dergisi

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ABSTRACT

Growing international pressure to reduce maritime emissions has intensified the search for cleaner propulsion alternatives within the shipping industry. Focusing on six sister container ships operating transatlantic routes, this research analyses 120 real-world voyages to compare the emission profiles of conventional fuels including Heavy Fuel Oil (HFO) and Marine Gas Oil (MGO) with alternative fuel Liquefied Natural Gas (LNG). Daily CO_2 emissions using traditional fuels averaged 111.3 tonnes, with nitrogen dioxide (NO_X) and sulphur dioxide (SO_X) emissions reaching 2,659.9 kg/day and 1,690.4 kg/day, respectively. LNG usage significantly reduced CO_2 by up to 32%, NO_X by 86%, SO_X by 99.95%, and particulate matter (PM) by over 90% while improving overall emission intensity. However, Methane (CH_4) emissions increased notably, averaging 354.2 kg/day, highlighting the need for methane slip mitigation. The Global Warming Potential (GWP) analysis revealed an average 23% reduction in climate impact with LNG. This research analyses different voyages of sister container ships on the same route to obtain realistic and comparable emission values, as well as demonstrating the impact of operational differences on emissions. Another novelty of this research is the not only calculation of emissions of N_2O, CH_4 and CO_2 but also a range of important harmful pollutants, highlighted by the International Maritime Organisation (IMO). By integrating fuel-specific emission factors and actual operational data, the study presents robust evidence supporting LNG's role as a transitional fuel toward achieving maritime sustainability goals. These insights offer strategic guidance for ship operators, regulators, and industry stakeholders navigating the pathway to low-carbon shipping.

Keywords: Conventional marine fuels, Container shipping, Global warming potential, Harmful emissions

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ÖZET

Denizcilik sektöründeki emisyonların azaltılmasına yönelik artan uluslararası baskı, denizcilik sektöründe daha çevreci sevk sistemlerinin arayışını yoğunlaştırmaktadır. Transatlantik rotalarda çalışan altı konteyner gemisine odaklanan bu araştırma, geleneksel yakıtların (HFO ve MGO) emisyon profilleri ile alternatif yakıtlardan Sıvılaştırılmış Doğal Gaz (LNG) ile karşılaştırmakta ve bu kapsamda 120 adet sefer verisi analiz edilmektedir. Geleneksel yakıtların kullanıldığı günlük CO_2 emisyonları ortalama 111.3 ton olurken, NO_X ve SO_X emisyonları sırasıyla 2659,9 kg/gün ve 1690,4 kg/gün olarak hesaplanmıştır. LNG kullanımı genel zararlı emisyon yoğunluğunu iyileştirirken CO_2'yi %32'ye kadar, NO_X'u %86'ya kadar, SO_X'u %99,95'e kadar ve partikül maddeyi %90'ın üzerinde önemli ölçüde azaltmıştır. Buna karşın LNG kullanımı, CH_4 emisyonları ortalama 354,2 kg/gün ile önemli ölçüde artarak metan kaymasının azaltılması ihtiyacını vurgulamıştır. Küresel Isınma Potansiyeli (GWP) analizi sonucunda, LNG kullanımı, küresel ısınma etkisinde ortalama %23'lük bir azalma sağladığını ortaya koymuştur. Bu araştırma, gerçekçi ve karşılaştırılabilir emisyon değerleri elde etmek için aynı rotadaki kardeş konteyner gemilerinin farklı seferlerini analiz etmekte ve ayrıca operasyonel farklılıkların emisyonlar üzerindeki etkisini göstermektedir. Bu araştırmanın bir diğer yeniliği, yalnızca N_2O, CH_4 ve CO_2 emisyonlarının değil, aynı zamanda Uluslararası Denizcilik Örgütü (IMO) tarafından vurgulanan bir dizi önemli zararlı kirleticinin de hesaplanmasıdır. Yakıta özgü emisyon faktörlerini ve gerçek operasyonel verileri entegre eden bu çalışma, LNG'nin denizcilikte sürdürülebilirlik hedeflerine ulaşmada bir geçiş yakıtı olarak rolünü destekleyen sağlam kanıtlar sunmaktadır. Bu bilgiler, deniz taşımacılığına düşük karbonlu yakıtlara geçiş yapmak isteyen ve bu yolda ilerleyen gemi operatörleri, düzenleyiciler ve sektör paydaşları için stratejik rehberlik sunmaktadır.

Anahtar sözcükler: Geleneksel deniz yakıtları, Konteyner taşımacılığı, Küresel ısınma potansiyeli, Zararlı emisyonlar

1. INTRODUCTION

Although maritime transport is the most environmentally friendly mode of transport per unit of cargo compared to land and air transport, ship-borne emissions pose a risk for environmental pollution since about 80% of world trade is transported by sea. The shipping industry's reliance on fossil fuels, particularly Heavy Fuel Oil (HFO) and Marine Gas Oil (MGO), continues to contribute significantly to global greenhouse gas (GHG) emissions (Al-Douri *et al*., 2022). The prediction of UNCTAD (2023) that global maritime trade will grow by around 2% from 2024 to 2028 also indicates that ship-related emissions such as sulphur oxides (SO_X), nitrogen oxides (NO_X), and carbon dioxide (CO_2), and particulate matter (PM) will increase further if extra regulatory measures are not taken. Without substantial improvements in energy efficiency and alternative fuel adoption, emissions from ships could undermine global decarbonisation efforts (McCarney, 2020).

In addition to the environmental impacts of these emissions, they also have negative effects on humans, such as premature deaths, cardiovascular and respiratory diseases (Chen and Yang, 2024; de Oliveira *et al*., 2019; Fu *et al*., 2023; Ma *et al*., 2023; Shu *et al*., 2022; Wang *et al*., 2025). Due to growing concerns about climate change and air pollution, the industry is under increasing pressure from various parties, such as authorities and policymakers, to employ more sustainable measures and develop efficient emission mitigation strategies (Haque and Ntim, 2018). In particular, the International Maritime Organisation (IMO) has set ambitious targets to reduce carbon intensity by at least 40% by 2030 and achieve net-zero GHG emissions by or around 2050 (Bullock *et al*., 2024). These targets necessitate the adoption of low-carbon fuels, improved operational efficiency, and technological advancements in ship design.
Within the maritime sector, emission reduction and Emission Control Areas (ECAs) regulations in the International Convention for the

Prevention of Pollution from Ships (MARPOL) and air and water quality in the United Nations Sustainable Development Goals are the most important concrete examples of international regulations (Van Roy *et al*., 2024; Zhou *et al*., 2024). However, the effectiveness of these regulations depends on compliance, enforcement mechanisms, and technological feasibility, particularly for long-haul shipping routes where fuel alternatives remain limited (Munim *et al*., 2023).

Fuel consumption is a primary determinant of ship-related emissions and is largely influenced by the vessel's technical configuration, as well as the operational characteristics of main and auxiliary machinery. In addition to these internal factors, a range of external conditions also significantly impact fuel efficiency, either positively or negatively. These include meteorological variables such as wind direction and intensity, oceanographic conditions such as currents and wave patterns, and operational parameters including voyage planning, load distribution, draft, and trim (Fan *et al*., 2022; Sang *et al*., 2023; Uyanık *et al*., 2020). In addition, slow steaming, hull coatings, and air lubrication systems are among the operational strategies used to enhance fuel efficiency and lower emissions (Balcombe *et al*., 2019; IMO, 2022b; Lion *et al*., 2020).

Another critical factor influencing ship-related emission levels is the type of fuel used. It has been observed that, in recent years, the maritime industry has increasingly turned to alternative fuel types as a means of reducing emissions. The alternative fuels that have attracted significant attention from researchers include Liquefied Natural Gas (LNG), methanol, biofuels, hydrogen, and ammonia (Balcombe *et al*., 2019; Xing *et al*., 2021). Considering these fuels, biofuels in particular have the potential to be used without modifying the existing fuel system, which significantly reduces initial investment costs. Moreover, given that biofuels can be derived from a wide range of feedstocks and methods, their production does not pose a risk of resource depletion. Additionally, most of countries and authorities provide incentives in this regard (Araújo *et al*., 2017; Bayraktar *et al*., 2023). On the other hand, LNG is one of the most widely used in theory and practice. As of 2022, approximately 5.39% of the vessels employed in maritime transport based on gross tonnage (GT) are capable of operating on LNG, and 30.2% of the vessels on order are either LNG-fueled or designed to be LNG-ready (DNV, 2022). It is considered an environmentally friendly fuel and has long been used as a supplementary energy source, with its role expanding in recent years to serve as the primary fuel for ships. LNG can be utilised directly in spark-ignited lean-burn gas engines and dual-fuel engines. While LNG offers low sulphur, CO_2, and pollutant content, and complies with Tier III NOx emission standards, it also presents several challenges. These include substantial storage requirements, the risk of CH_4 leakage, and complications associated with its liquefaction, storage, and transportation. Nevertheless, LNG benefits from a more mature supply chain and distribution infrastructure compared to other alternative fuels (Bilgili, 2021; Zincir and Arslanoglu, 2024).

Reducing fuel consumption and the associated emissions is essential for ships to meet both their environmental sustainability obligations and regulatory compliance requirements. In this context, the present research aims to conduct a comprehensive examination of the types and quantities of fuels consumed by ships during voyage operations, alongside the emissions generated. Furthermore, the study seeks to estimate the emissions that would result from the use of alternative fuels. By incorporating real-world operational data, this research offers a robust analysis of fuel consumption patterns, emission intensities, and the potential environmental benefits associated with the adoption of alternative fuels in the maritime sector.

In this research, 20 voyages of six sister container ships operating along the same voyage line were examined in the first step. Emissions resulting from the use of HFO and MGO were analysed across a total of 120 voyages. In addition to these fuel-specific emissions, the values of CO_2, N_2O, and CH_4, which are significant GHGs, were specifically calculated for each ship. In addition, calculations were performed for harmful emissions such as carbon monoxide (CO), non-methane volatile organic compounds (NMVOC), PM, fine particulate matter ($PM_{2.5}$), black carbon (BC), NO_X, and SO_X emitted by ships. Furthermore, this study included a comparative evaluation of emissions under conventional fuel scenarios and an alternative fuel scenario involving the use of LNG, thereby highlighting the potential outcomes in terms of emission reduction.

Finally, the emission values that would result from the use of LNG, one of the alternative fuels, in these ships were calculated, and the Global Warming Potential (GWP) of LNG was compared with that of conventional fuels. A detailed representation of the research process is provided in Figure 1.

This research adopts a voyage-specific and ship-specific approach, offering a comprehensive and realistic analysis of emissions by utilising data from 20 comparable voyages conducted by six sister container ships operating along the same route. This contrasts with previous studies that typically rely on generic emission factors or aggregated fleet-level data. It also enables the observation of the impact of operational differences on emissions in these ships. Another important novelty of this research is that it includes the calculation of not only CO_2 but also important emissions such as N_2O and CH_4. Moreover, this research also includes the calculation of a wide range of harmful pollutants, including CO, NMVOC, PM, $PM_{2.5}$, BC, NO_X, and SO_X, whose importance is also highlighted by the IMO. This research combines detailed emission calculations, mutual fuel scenario modelling, and GWP assessments in the context of real operational processes to present empirical results on emission reduction strategies and alternative fuels. The insights derived from this study can also contribute to policy development, investment decisions, and strategic planning for a more sustainable maritime sector.

The remainder of this research is structured as follows. Section 2 presents the methodology employed in the study. Section 3 outlines the results obtained from the analysis. Section 4 concludes the research by providing a discussion of the findings, interpretations, recommendations, and identified limitations.

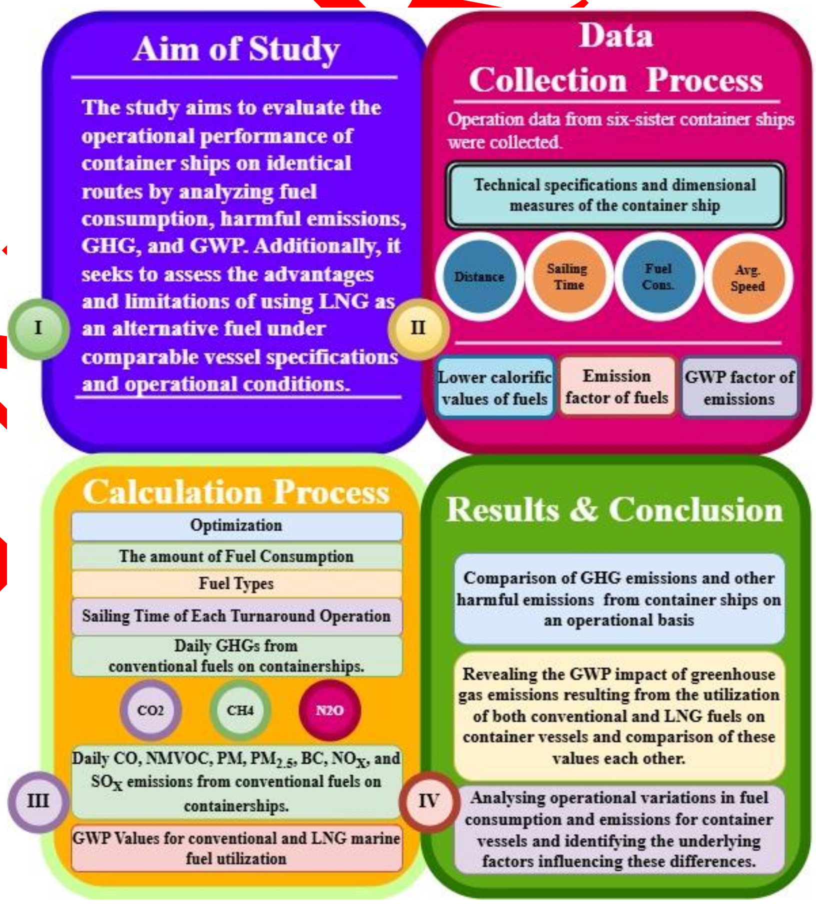

Figure 1. Flowchart of research.

2. METHODOLOGY

Container ships have gained increased importance in maritime transport in recent years due to their flexibility, integrated operation with other transport modes, and numerous other features. Within the scope of this matter, the basis of this study is rooted in data obtained from six container ships. Six container ships have the same technical specifications and dimensional measures and are classified as sister ships. Comprehensive details are shown in Table 1 for one of the container ships.

These container ships are primarily deployed on trans-Atlantic trade routes, where liner shipping is most concentrated and holds the highest market share. Twenty sets of data, comprising a total of 120 voyages, were collected from each ship operating along this route. A sample dataset is presented in Table 2.

Table 1. Technical specifications and dimensional measures of the container ship

Parameters	Description/Value	Unit
Type of ship	Container carrier	-
Capacity	1880	TEU
Service speed	19.5	Knots
Power of main engine	15820	kW
Generators	3*800	kW
L_{OA}	182.85	M
L_{BP}	171	M
Beam (moulded)	28	M
Depth (moulded)	16.1	M
Draft (designed)	11	M
Hight (from keel)	49	M
Gross tonnage	21092	Tonnes
Net tonnage	8600	Tonnes
Summer DWT	26646	Tonnes
Lightweight	9001	Tonnes
Displacement summer	35648	Tonnes

Table 2. Sample dataset of research

Operation No	Distance [nm]	Average Speed [knots]	Sailing Time [days]	HFO Consumption at Sailing Time [tonnes]	MGO Consumption at Sailing Time [tonnes]
[1]	12852	13.99	38.29	1029.62	109.82
[2]	12921	14.46	37.23	943.08	92.03
[3]	11611	15.15	31.93	1031.3	117.3
[4]	11696	14.75	33.05	1124.9	121
[5]	12651	14.63	36.03	1294.4	107.5
[6]	13008	15.25	35.53	1303.2	128.7
[7]	13095	14.9	36.61	1409.4	110.7
[8]	12729	14.8	35.83	1451.9	120.6
[9]	12687	15.42	34.29	1204.8	100.8
[10]	13082	15.81	34.48	1168.2	77.6
…	…	…	…	…	…

This dataset includes information on distance travelled, average speed, sailing time, and total fuel consumption. It is utilised to calculate emissions and assess their environmental impacts from container ship operations over a defined period. Given the current propulsion and power configurations of container ships, HFO and MGO are employed as the primary fuels for both main and auxiliary engines. This study also evaluates the environmental viability of LNG as an alternative fuel for container ships. Accordingly, in addition to HFO and MGO, the emission factors and lower calorific values for LNG are provided in Table 3.

Table 3. Lower calorific values and emission factors of HFO, MGO and LNG (IMO, 2020b, 2022a)

Fuel Types	LCV (kJ/kg)	CO_2	CH_4	N_2O	NO_X	CO	NMVOC	SO_X	PM	$PM_{2.5}$	BC
		(kg pollutant/tonne fuel)									
HFO	40200	3114	0.05	0.18	75.9	2.88	3.2	50.83	7.55	6.94	0.26
MGO	42700	3206	0.05	0.18	56.71	2.59	2.4	1.37	0.9	0.83	0.38
LNG	48000	2755	11.96	0.1	13.44	3.97	1.59	0.03	0.11	0.1	0.019

NO_X, SO_X, CO_2, and PM emissions are among the most critical pollutants in maritime transportation, and limitations have been imposed on emission rates and their quantities in both global regions and ECAs. This study assesses additional emissions beyond those critical ones for each fuel type, considering the factors outlined in Table 3. LNG differs from conventional marine fuels in terms of pollutant emission factors while also possessing a relatively higher Lower Calorific Value (LCV). Among the emission types outlined in Table 3, CO_2, CH_4, and N_2O emissions cause global warming. However, it should be noted that each type of emission has a different adverse impact on global warming and disrupts the global sustainable development goals. The GWP impact values of the specified emissions have been expressed in Figure 2 (The Intergovernmental Panel on Climate Change (IPCC), 2025).

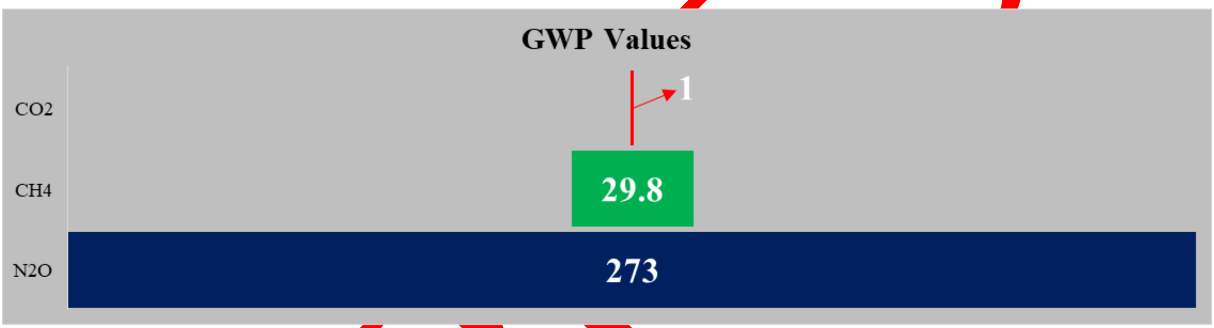

Figure 2. GWP values of the specified emissions (The Intergovernmental Panel on Climate Change (IPCC), 2025).

The emissions released from marine vessels are basically calculated on an energy-based or fuel-based basis.

$$E = m \cdot LCV \quad (1)$$

$$m_{LNG} \cdot LCV_{LNG} = m_{HFO} \cdot LCV_{HFO} = m_{MDO} \cdot LCV_{MDO} \quad (2)$$

$$\text{GHG emissions} \rightarrow \left(g_{CO_2}; g_{CH_4}; g_{N_2O}\right) \quad (3)$$

$$\text{GHG emissions} \rightarrow \text{EF\_CO}_2 * m_{HFO;MDO;LNG} + \text{EF\_CH}_4 * m_{HFO;MDO;LNG} + \text{EF\_N}_2\text{O} * m_{HFO;MDO;LNG} \quad (4)$$

$$\text{Total GHG}_{CO_2eq} = \text{GWP}_{CO_2(100y)} * g_{CO_2} + \text{GWP}_{CH_4(100y)} * g_{CH_4} + \text{GWP}_{N_2O(100y)} * g_{N_2O} \quad (5)$$

In these formulas, E is produced energy, m is amount of fuel consumed, LCV is Lower calorific value of each fuel, EF is Emission factors for each fuel, g refers to the emission amounts of fuels (Greenhouse Gas Protocol, 2024; IMO, 2020a).

Energy-based emissions are quantified using the LCV, corresponding emission factors, and GWP values, as defined in Table 3 and illustrated in Figure 2, in accordance with the methodologies outlined in Equations (1) through (5). In the calculation of the Total GHG_{CO_2eq}, both the quantities of emission and the GWP factors are considered.

Beyond the system descriptions aspects outlined in the methodology section, the assumptions and limitations made, and the calculations conducted during the computational phase are detailed step by step as follows:

- ➢ Datasets were obtained from six container ships, each contributing a minimum of 20 recorded turnaround operation entries, resulting in a total of 120 data points. From this comprehensive dataset, the specific data required for emission calculations were extracted. The most essential parameters included distance travelled, average speed, sailing time, and the consumption of HFO and MGO during sailing, as used in both main and auxiliary engines.

- ➢ All key parameters were recalibrated based on the average distance travelled to strengthen the reliability of comparisons concerning harmful emissions, GHG outputs, and GWP impact. This standardisation was applied because all the container ships analysed operate along the same trans-Atlantic route.
- ➢ The amounts of GHG-causing gases were calculated daily based on fuel consumption amounts, fuel type, sailing time, and emission coefficients. Subsequently, the daily emissions of other pollutants, with no GHG impact, were calculated.
- ➢ Considering the LCVs of the specified fuels, the emissions resulting from the same operations using LNG fuel were calculated. Similar calculations were conducted for LNG fuel utilisation, first assessing GHG-related emissions, followed by the daily computation of other pollutant emissions.
- ➢ In the last stage of the calculations, the global warming impacts were calculated and compared by analysing the amounts and GWP of GHG gases from both conventional fuels and LNG.

3. RESULTS AND DISCUSSIONS

Fuel consumption values and sailing distances for the six container ships were obtained from data recorded during each turnaround operation. A total of 120 voyage records were collected, with 20 data points from each ship. All six container ships operated along the same shipping routes. Although the sailing time, travelled distance, and fuel consumption values are generally similar, variations are observed due to differences in vessel characteristics and operational conditions. The average distance recorded across the 120 turnaround operations is 12858 NM for the six container ships. Figure 3 illustrates the fuel consumption and sailing time for each vessel, interpolated to the average distance for consistency in comparison.

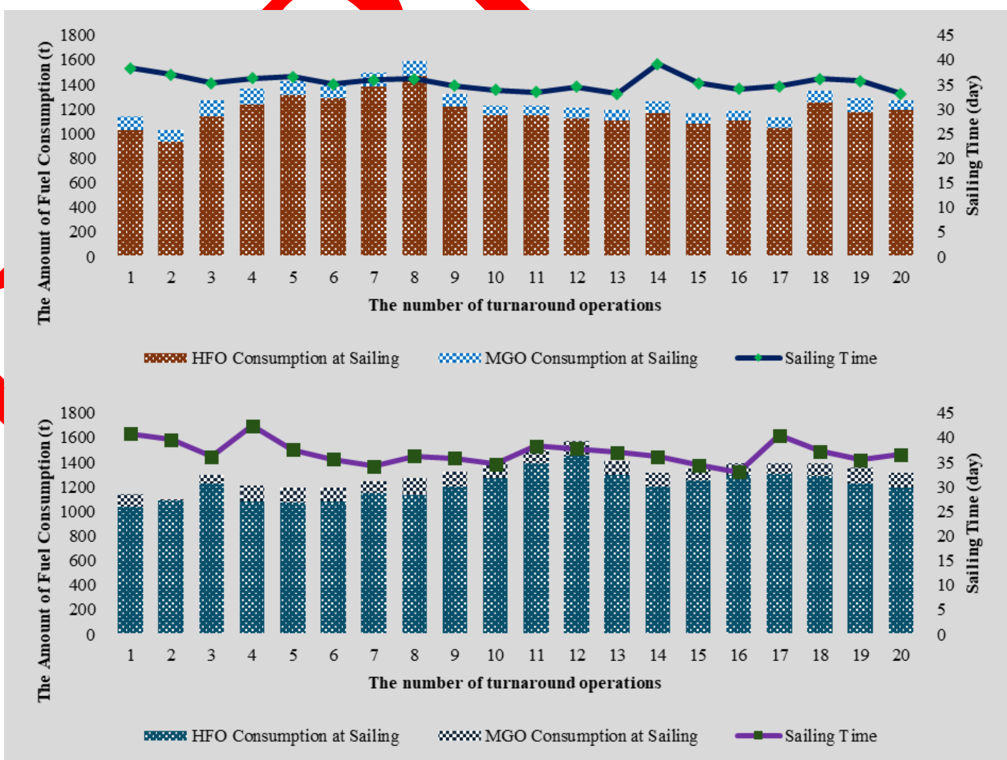

Figure 3. HFO-MDO Consumption and sailing time of the container ships

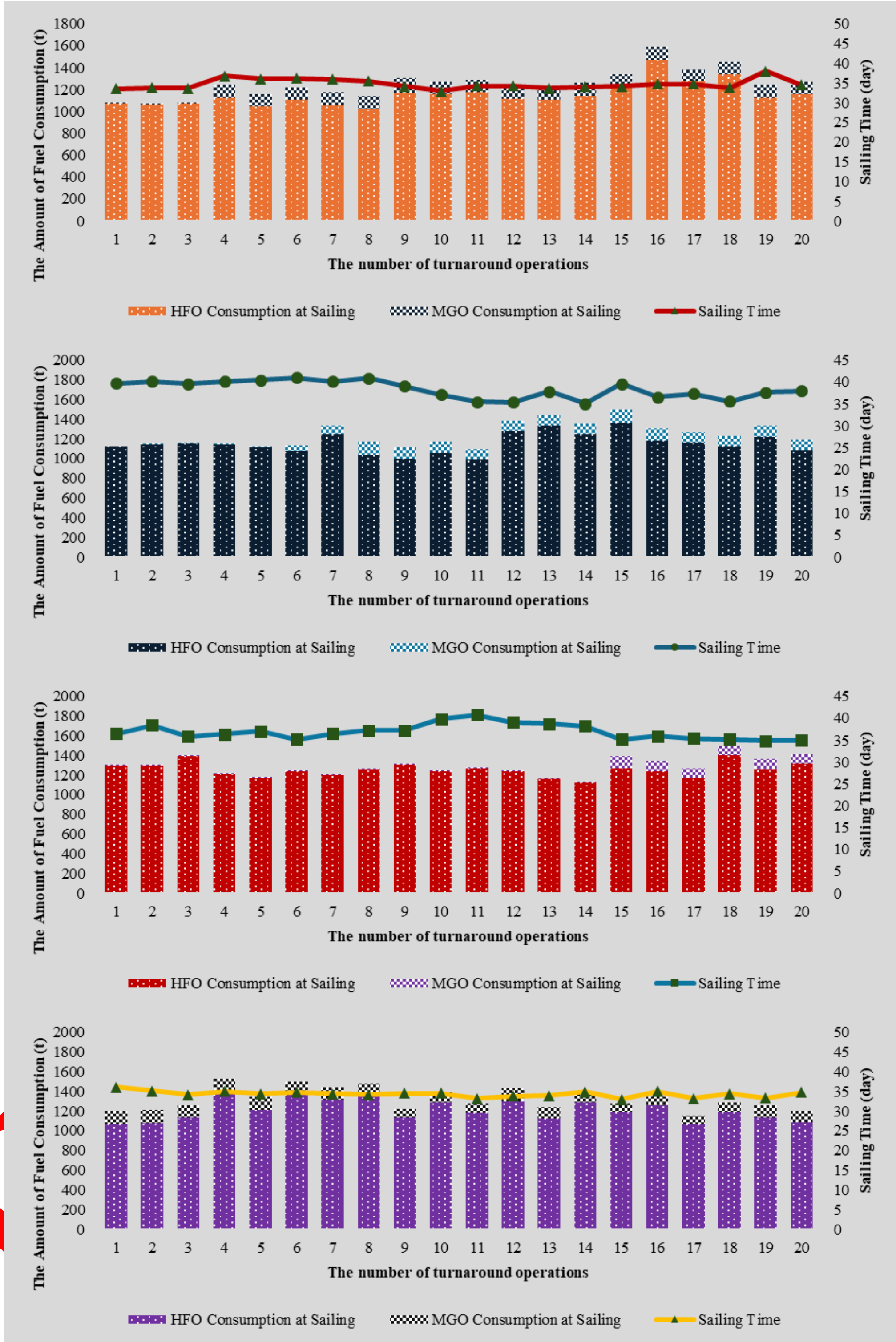

Figure 3. (Continued)

Based on the 20 recorded turnaround operations of Container Ship I, the average sailing time was calculated as 35.46 days, with the minimum and maximum sailing times recorded at 33.14 and 39.17 days, respectively. During these operations, HFO consumption ranged from 938.54 tonnes to 1466.71 tonnes, with an average consumption of 1179.55 tonnes. In addition to HFO, MGO was consumed for auxiliary engine operations, with recorded values ranging from 76.28 to 133.03 tonnes. The average MGO consumption across the voyages was 100.36 tonnes.

The analysis of the operational data for Container Ship II indicated that the vessel's sailing duration ranged from 33.01 to 42.40 days. Based on 20 recorded turnaround instances, the average sailing time was approximately 37 days. During these operations, the consumption of HFO ranged between 1042.89 and 1452.89 tonnes, with an average consumption of 1213.87 tonnes. Furthermore, the maximum recorded usage of MGO in auxiliary engines was 131.96 tonnes, while the overall average consumption was 104.57 tonnes.

In comparison with the operational data from Container Ships I and II, Container Ship III exhibited a lower fluctuation rate in sailing times, recorded at approximately 15.5%. The minimum, maximum, and average sailing durations for Container Ship III were 32.95 days, 38.06 days, and 34.78 days, respectively. In terms of fuel consumption, the lowest, highest, and average HFO usage values were 1024.24 tonnes, 1474.87 tonnes, and 1152.66 tonnes, respectively. The fluctuation in HFO consumption for Container Ship I was approximately 56.2%, representing the highest variability among the three vessels. The second-highest fluctuation, at 43.9%, was observed in the operational data of Container Ship III. Additionally, the average MGO consumption by auxiliary engines during sailing operations for Container Ship III was 97.64 tonnes, with a maximum recorded value of 137.02 tonnes.

For Container Ship VI, where the recorded data exhibit minimal variation compared to those of Container Ship III, the optimised sailing times ranged from 35.06 to 41.04 days, with an average duration of 38.37 days. The HFO consumption during these voyages varied between 995.32 and 1366.07 tonnes, with an average consumption of 1155.81 tonnes. Additionally, the average MGO consumption by the auxiliary engines was recorded at 82.69 tonnes.

According to the optimised operational data for Container Ship V, sailing times ranged from 34.93 to 40.87 days, with an average duration of 36.94 days. The fluctuation rates in optimised sailing times for both Container Ships V and VI were approximately 17%, representing the second lowest variability among the container ships analysed. During the sailing period, HFO consumption by the main engine of Container Ship V ranged from 1124.67 to 1399.87 tonnes, with a fluctuation rate of 24.5%. Although this rate is relatively high in absolute terms, it remains the lowest among all recorded operations. Furthermore, the average MGO consumption was recorded at 32.99 tonnes, which is lower than the corresponding values for the other five container ships.

The sailing times of Container Ship VI ranged from 32.95 to 36.07 days, based on the analysis of 20 optimised turnaround records. The fluctuation rate in optimised sailing time was approximately 9.5 percent, representing the lowest variability among all container ships examined. In contrast, the fluctuation rate of main engine fuel consumption was not as low as that of Container Ship V. It was approximately 30.6 percent, which is the second lowest rate observed. The total HFO consumption during these operations ranged from 1063.63 to 1389.32 tonnes. The average HFO and MGO consumptions were recorded as 1209.16 tonnes and 112.90 tonnes, respectively.

The consumption of HFO and MGO during the sailing of container ships is critical for supplying the necessary energy to main and auxiliary engines; however, it also contributes to the emission of greenhouse gases. CO_2, N_2O, and CH_4 are the primary emissions associated with this impact. Figure 4 presents the average daily greenhouse gas emissions resulting from the use of conventional marine fuels across the analysed container ships.

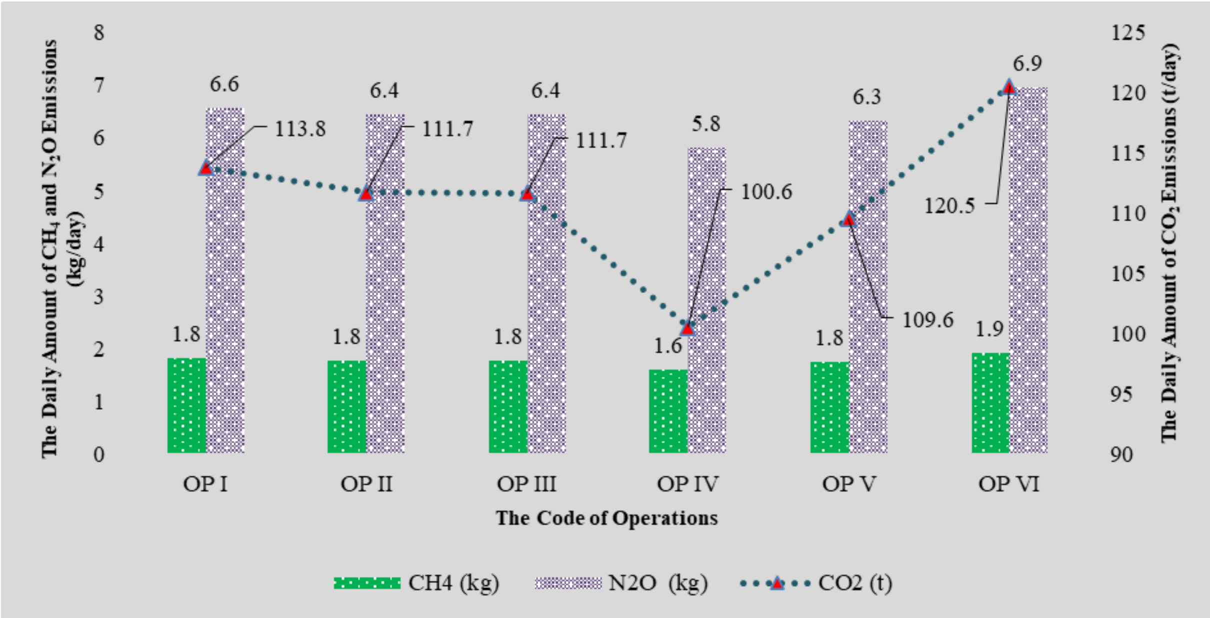

Figure 4. Daily GHG emissions from conventional fuels on container ships

Since the carbon factor of conventional fuels is relatively higher than that of alternative marine fuels, the daily amount of CO_2 emissions exceeds three times the daily fuel consumption. The ratio of CO_2 emissions with a fluctuation of 16.5 % varied between 100.6 t/day and 120.5 t/day, considering the number of 120 optimised voyage data. The CO_2 emissions of six container ships were 111.3 tonnes/day. Nevertheless, in addition to CO_2 emissions, the amount of CH_4 and N_2O emissions causing GHG are lower than the total fuel consumption of the container ships because their emission coefficients are quite low compared to CO_2. CH_4 emissions varied between 1.6 kg/day and 1.9 kg/day with minor fluctuations. On the other hand, N_2O emissions varied between 5.8 kg/day and 6.9 kg/day, and the average was 6.4 kg/day. In addition to GHGs, the use of conventional fuels causes emissions of other harmful gases, which are CO, NMVOC, PM, $PM_{2.5}$, BC, NO_X, and SO_X, on container ships.

Among the emissions specified in Figure 5, especially the amount of daily emitted NO_X and SO_X emissions are the highest ones, and their averages were 2659.9 kg/day and 1690.4 kg/day, respectively. These emissions are followed by PM, $PM_{2.5}$, NMVOC, CO, and BC, and their average emission rates as kg/day were 252.8, 232.4, 112.2, 102, and 9.6, respectively. Although conventional fuels such as HFO and MGO are currently the most utilised fuels in marine vessels, the use of LNG has become quite widespread in the last decade. If LNG fuel were utilised instead of conventional fuels in both main and auxiliary engines, the average daily LNG consumption based on container ship operations would be 28.18 t/day, 27.64 t/day, 27.68 t/day, 25.22 t/day, 28.69 t/day, and 29.62 t/day, respectively. Based on these consumption levels, GHG emissions from container ships are presented in Figure 6 on a daily basis.

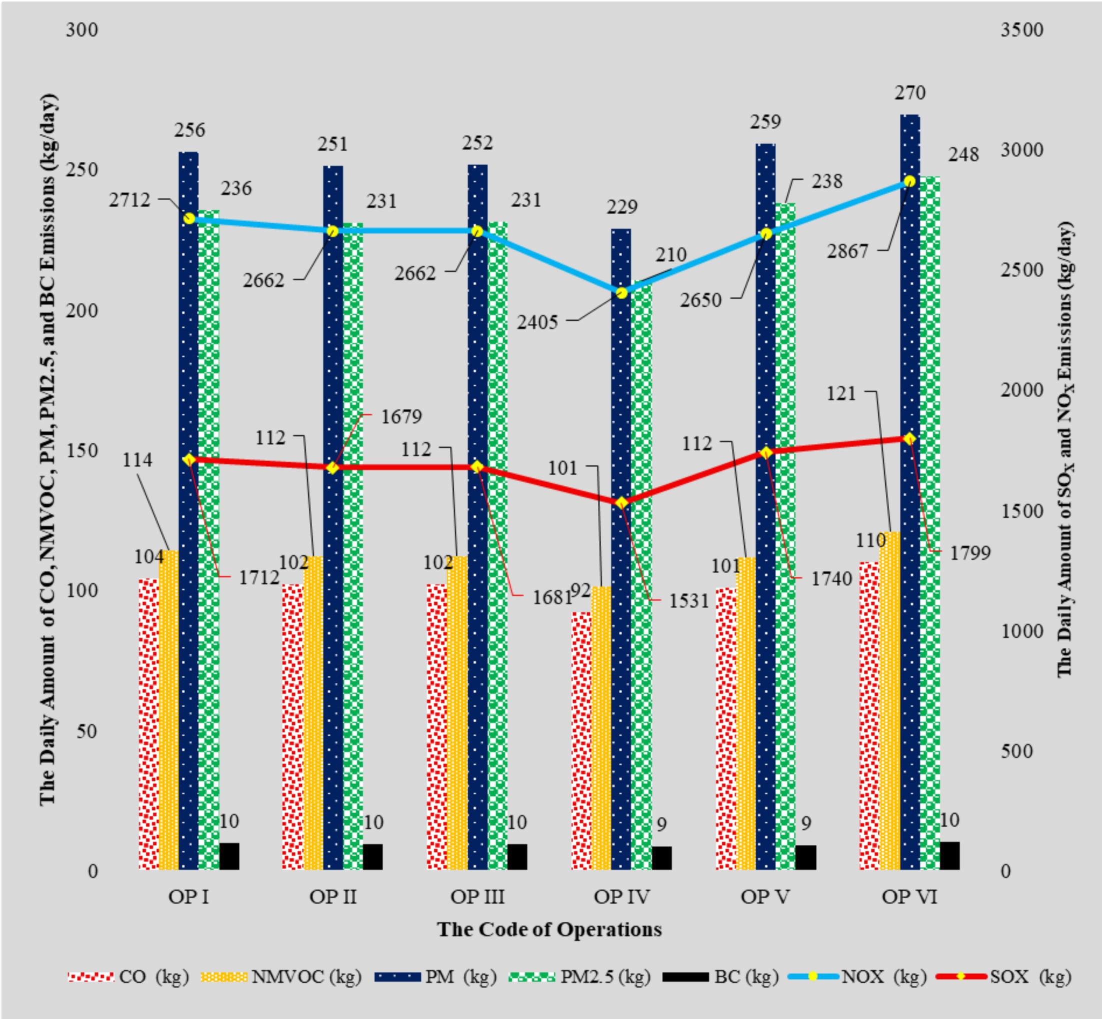

Figure 5. Daily CO, NMVOC, PM, $PM_{2.5}$, BC, NO_X, and SO_X emissions from conventional fuels on container ship

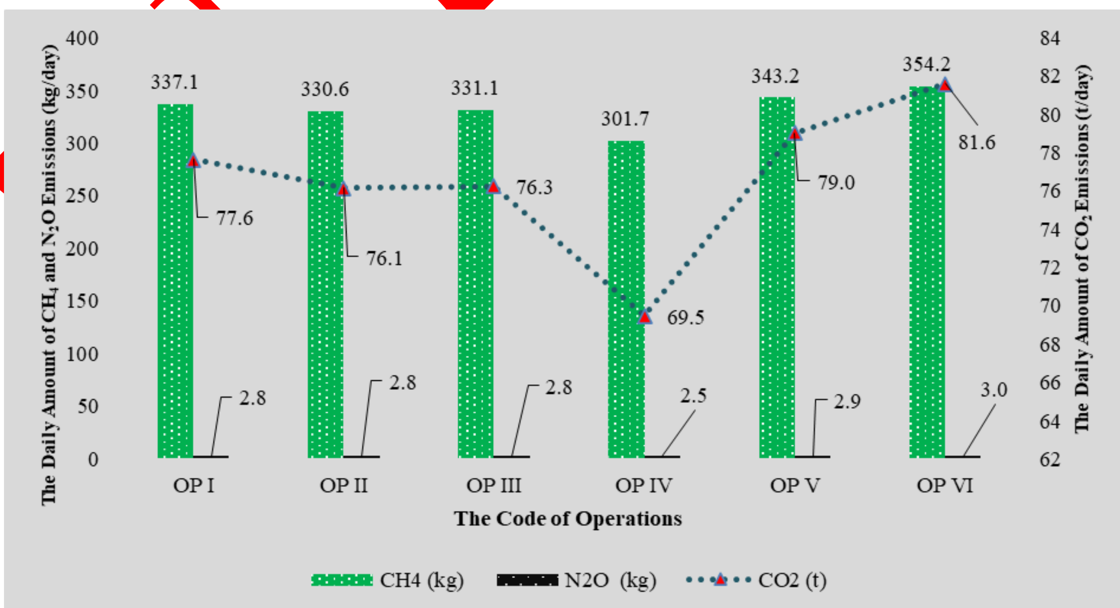

Figure 6. Daily GHG amount of LNG

The LNG utilisation reduced CO_2 emissions, ranging from 28% to 32%, compared to conventional fuel used on container ships. However, the daily CH_4 emissions increased enormously and reached 354.2 kg/day because 1.9 kg/day is the highest one when conventional fuel is utilised in container ships. N_2O emissions ranged from 2.5 to 3 kg/day, which are relatively lower than rates obtained from the use of conventional fuels. The impact of LNG utilisation on other emissions is represented in Figure 7.

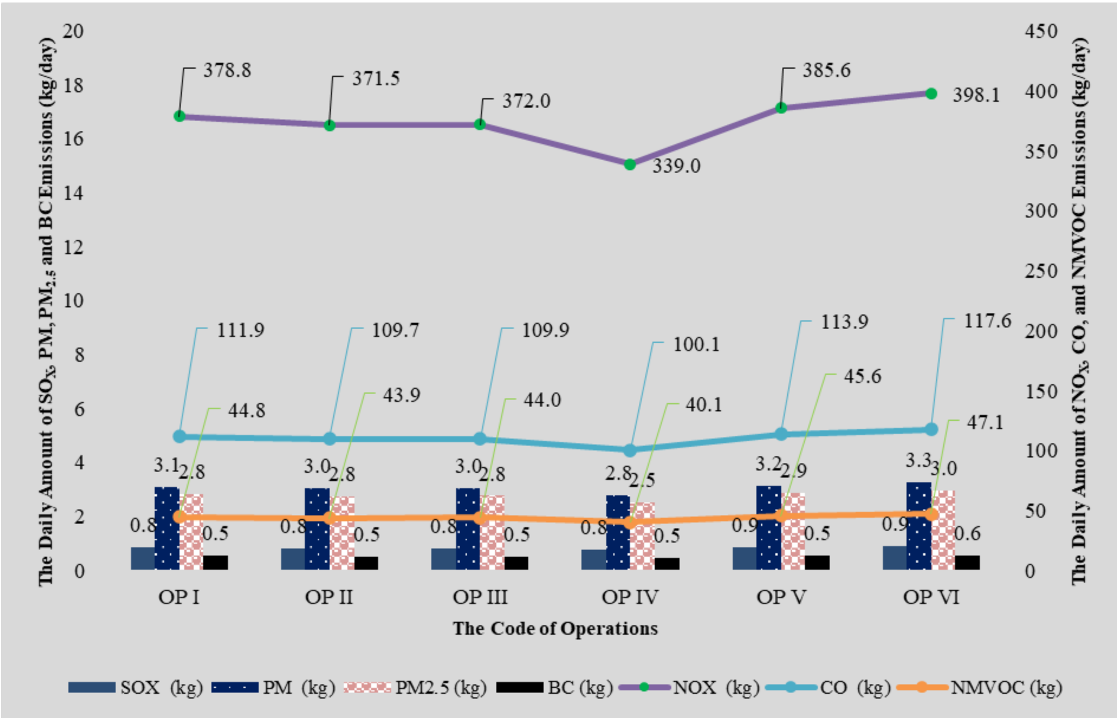

Figure 7. Daily CO, NMVOC, PM, $PM_{2.5}$, BC, NO_X, and SO_X emissions of LNG.

The use of LNG significantly reduces both NO_X and SO_X emissions and almost eliminates SO_X emissions with 99.95%. The average daily NO_X emissions of container ships ranged from 339 kg/day to 398.1 kg/day with the LNG utilisation, and the reduction rate is roundly 86% compared to conventional fuels. In addition, the utilisation of LNG provides reductions exceeding 90% in PM, $PM_{2.5}$, and BC emissions. In terms of NMVOC emissions, the reductions are around 60% rates, and 44.3 kg emissions are generated per day on container ships. These findings are consistent with previous studies that have reported reductions in CO_2, NO_X, and SO_X emissions when LNG is used instead of conventional marine fuels (Korkmaz *et al.*, 2023). The observed emission reductions, particularly in PM and SO_X, also align with the reported performance of LNG-powered container ships in comparable operational scenarios (Heikkilä et al., 2024).

The GWP coefficients of the most known GHG emissions are quite different. Considering these coefficients, the GWP effects of both conventional fuels and LNG fuel are calculated and depicted in Figure 8 with GWP reduction rates.

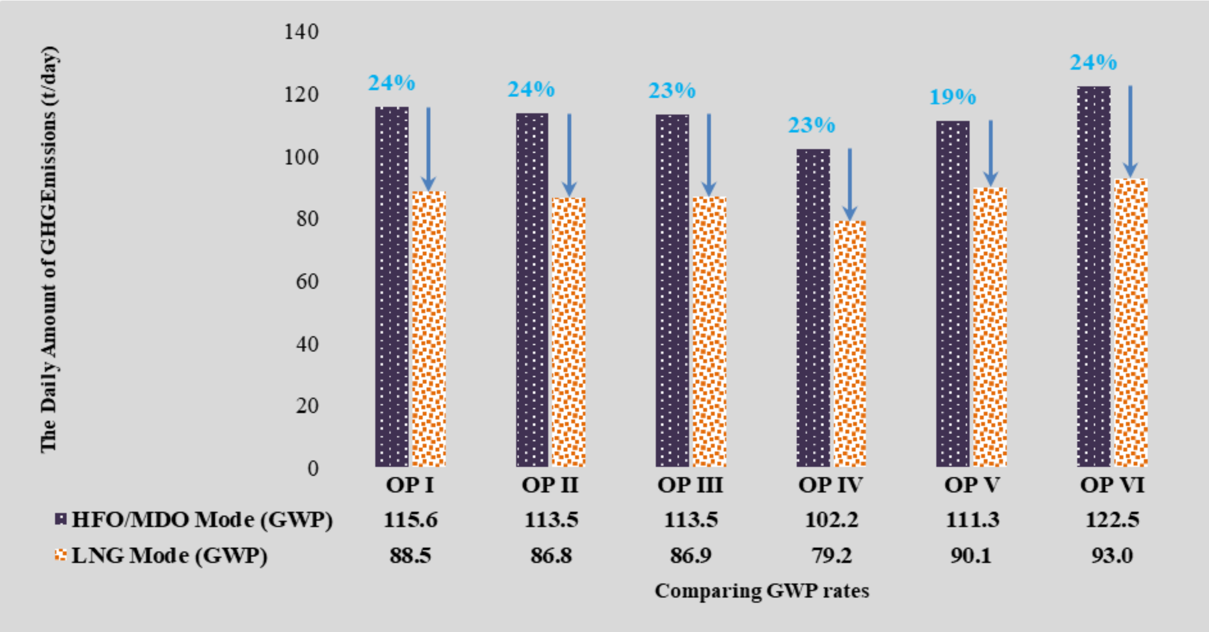

Figure 8. GWP Reduction rates.

The fuel consumption, fuel types, and their respective GWP coefficients are considered in the calculation of the GWP resulting from the operation of the six sister container ships. Under optimised existing operations of the container ships using conventional fuels, the daily GWP values range from 102.2 to 122.5. With the utilisation of LNG, these values decrease significantly, ranging from 79.3 to 93. The corresponding GWP reduction rates vary between 19% and 24%, with an average reduction of approximately 23%. Compared to similar research on GWP impacts of LNG versus conventional fuels, the reduction rates in this study are slightly higher than some port-based analyses but comparable to full-voyage simulations under dual-fuel (Al-Douri *et al.*, 2022).

4. CONCLUSIONS

This research aimed to evaluate the operational performance of six sister container ships operating along the same route by analysing 120 real voyage records and calculating the emissions resulting from fuel consumption during these voyages. Additionally, the GWP values associated with the use of conventional fuels were calculated and compared with the projected GWP values assuming LNG utilisation. Analysis of the voyage records revealed significant variations in fuel consumption levels, both between different ships and across individual voyages of the same ship. As these variations directly influenced the volume of emissions produced, it was essential to identify the factors contributing to increased fuel consumption. Voyage scenarios in which the ships utilised LNG as fuel were conducted to evaluate the fuel consumption and emissions that would have occurred if alternative fuels had been used in place of conventional fuels. The results showed that LNG significantly reduced emission levels, especially of CO_2, NO_X, and SO_X. Therefore, it can be concluded that shipowners and operators may consider LNG as a viable alternative fuel to support environmental sustainability in line with regulatory requirements and corporate social responsibility. However, to optimise commercial operations, it is essential to assess both the advantages and disadvantages of LNG during the investment decision-making process.

Due to limitations in data availability and time constraints, this study was restricted to the analysis of sister container ships. For future research, it is recommended that emission values be calculated for ships of varying sizes and types, to assess differences in their environmental impacts. Furthermore, as demonstrated in this study, a detailed examination of fuel consumption variations across identical voyages can inform the development of preventive measures, which would be beneficial both for enhancing environmental sustainability and contributing to the academic literature.

AUTHORSHIP CONTRIBUTION STATEMENT

Coşkan SEVGİLİ: Conceptualisation, Investigation, Data curation, Formal analysis, Methodology, Validation, Writing – original draft, Writing – review & editing. **Murat BAYRAKTAR:** Conceptualisation, Investigation, Data curation, Formal analysis, Methodology, Validation, Writing – original draft, Writing – review & editing. **Onur YÜKSEL:** Conceptualisation, Investigation, Visualisation, Methodology, Validation, Writing – original draft, Writing – review & editing. **Alper SEYHAN:** Conceptualisation, Investigation, Visualisation, Methodology, Validation, Writing – original draft, Writing – review & editing.

CONFLICT OF INTERESTS

The author(s) declare that for this article they have no actual, potential or perceived conflict of interests.

ETHICS COMMITTEE PERMISSION

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