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Liquefied Natural Gas (LNG) as a Transitional Choice Replacing Marine Conventional Fuels (Heavy Fuel Oil/Marine Diesel Oil), towards the Era of Decarbonisation

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Abstract: As environmental regulations on sulphur emissions become more severe, the maritime sector is looking for alternative solutions. This study evaluates greenhouse gas (GHG) reduction alternatives and their combined ability to decarbonise international transport. Liquefied natural gas (LNG) is becoming widely used, reducing CO_2 emissions by 20–30 percent, while it has similar action in other emissions such as SO_X. Although costs are attractive, methane slip, which depends on the engine type, reduces GHG gains. Replacing conventional fuels such as heavy fuel oil and marine diesel oil with alternative ones is an effective method to decrease SO_x emissions. Liquefied natural gas is highly appreciated as an alternative fuel for maritime transportation. In this frame, the possibility of using alternative fuels, such as LNG, to reduce NO_x, CO_2 and SO_x emissions in Heraklion Port, including certain regionally defined waters, over the life of the vessel will also be explored. The study is conducted for ships calling at Heraklion Port and using alternative fuel such as LNG in different modes (cruising, hotelling, manoeuvring). A fuel-based emission reduction factor, rE_{if}, is defined in relation to the comparison of two different fuels: conventional (heavy oil, marine diesel) and alternative fuels (LNG). The bottom-up method is used for this data analysis. This study, by defining the reduction of several emissions with the use of LNG, indicates that it is actually an efficient transitional fuel to lead international transport to decarbonisation.

Keywords: decarbonisation target; GHG emissions; HFO; MDO; LNG; transitional fuel; alternative fuels

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1. Introduction

Maritime transport plays an important role in international trade and is a major contributor to air pollution and climate change. Air pollution, caused primarily by ships worldwide, appears to be a major source of anthropogenic emissions [1], particularly oxides such as (SOx), (NOx), (CO_2), and particulate matters (PM) [2–5]. As shown in Figure 1, limits on SOx emissions have been tightened by the International Maritime Organization in response to the impact of these pollutants. The International Maritime Organization (IMO) agreed at its 70th MEPC meeting in October 2016 to reduce sulphur emissions from 3.5% to 0.5% [6–8].

Alternative technologies and alternative fuels are the two main ways to reduce sulphur oxides to meet stringent standards and fines. Scrubbers, exhaust gas recirculation (EGR), and selective catalytic reduction (SCR), as well as others [9–11], represent alternative technologies, while natural gas, hydrogen, biofuels, electricity, nuclear energy, ammonia, and methanol are alternative fuels [12,13].

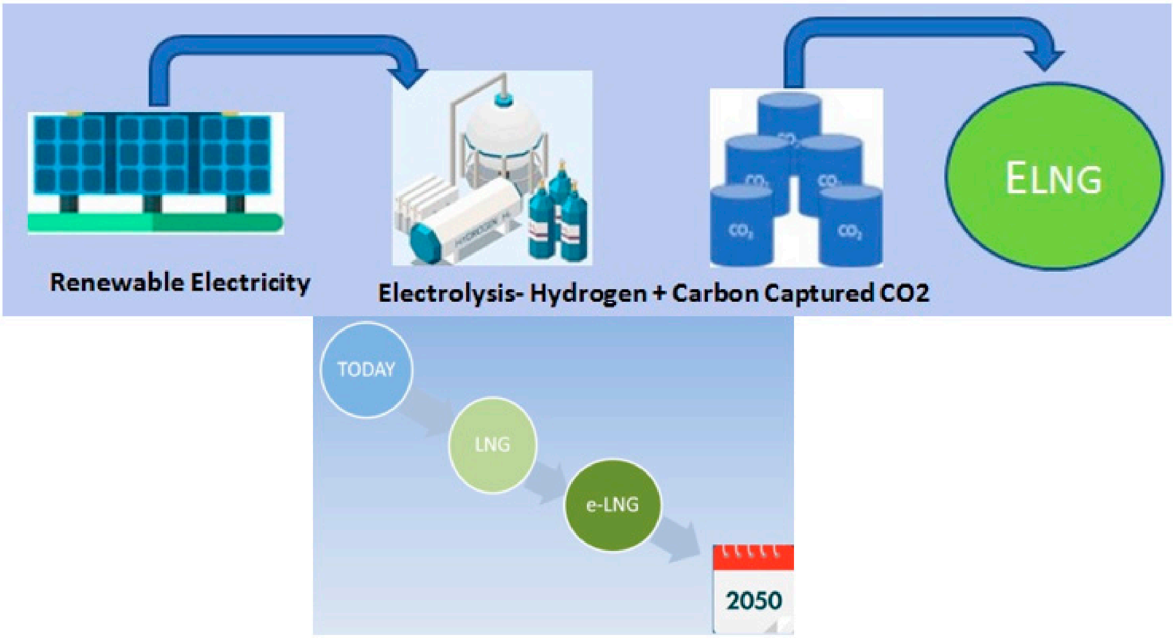


Figure 1. The decarbonisation journey of shipping with green methane.

The most common alternative technology for reducing SO_x emissions is the use of scrubbers (gas cleaning systems). Scrubbers have increased their competitiveness in comparison to high-priced low-sulphur fuels, while it is noted that the combination of heavy fuel oil (HFO) with scrubbers results in the lowest cost for big ships [14–16]. Scrubbers also have to deal with two important issues. Firstly, an increasing number of ports are considering prohibiting or have already forbidden discharging exhaust water from scrubbers into the sea, posing a threat to the environment. As a consequence, several water basins ban open-loop scrubbers, the least costly solution of scrubber. This is an expensive headache for shipowners who must comply with sulphur restrictions. Secondly, during the period of COVID-19, the difference in price between high-sulphur heavy fuel oil (HSFO) and LSFOs shrank, reducing the economic benefit of scrubbers. The two most common alternative technologies apart from the scrubbers are selective catalytic reduction (SCR) and exhaust gas recirculation (EGR), which are out of the scope of this study [17].

LNG, on the other hand, is the most commonly used alternative fuel in the marine industry and is preferred for newly built boats since the LNG price is lower than the HFO price, despite the energy crisis, while the LNG retrofitting cost for existing vessels is usually too expensive [18]. It is mainly used in emission control areas due to its relatively low concentration of sulphur, carbon, and nitrogen. Livanos et al. [19] compared a diesel engine (with and without a waste heat recovery system) to a dual-fuel engine (marine diesel oil and LNG as a pilot fuel). Even though the use of LNG lowers operating expenses, decreases emissions, and increases the efficiency of the power system, the authors highlight significant issues such as high investment costs, a shortage of LNG facilities at ports, and safety concerns. These concerns were also raised by Schinas and Butler [20], who discovered that ships travelling on fixed routes had a greater potential for LNG propulsion. Another issue with LNG fuel is what is known as "methane slip", which occurs when unburned methane from the fuel is released in combination with the exhaust gas. On the other hand, modern two-stroke engines almost eliminate this problem [8,21]. At the moment, LNG engines have a methane leakage between 2% and 5% of total throughput, but reports from high-pressure two-stroke engines operating on dual fuel indicate a far lower leakage [8].

Given that LNG contains no sulphur, SOx emissions are probably avoided. Although dual-fuel engines need a modest quantity of oil-based fuel to ignite, they may decrease emissions of SOx by 90–99 percent when compared to HFO [22]. Additionally, particulate particles (PM) are on the verge of extinction [23].

NOx emissions from a low-pressure dual-fuel engine system are much lower than those from fuels in a liquid form. Emissions of NOx are proportional to the temperature of combustion because greater temperatures generate more NOx. In contrast to HFO, a lower fuel-to-air ratio obtained by certain LNG engines and a larger percentage of gas in a dual-fuel engine decreases the temperature of combustion, resulting in a 75–90% reduction in NOx emissions [22]. Nonetheless, a trade-off exists between emissions of NOx and methane: although low temperatures result in reduced NOx emissions, higher temperatures result in less methane slip. While methane slip could be lowered to 0.2 percent of throughput in high-pressure dual-fuel engines, without further exhaust controls, emissions of NOx will not meet Tier 3 norms [22,24].

In dual-fuel engines, the fuel mix and emissions of CO_2 are approximately linear, while only a fuel blend of less than 30% diesel may result in significant reductions in NOx emissions. As a consequence, without the need for further treatment of exhaust gases, such as selective catalytic reduction (SCR), the NOx emission limitations specified in the NOx ECAs will result in a decrease in the quantity of oil fuel used.

The role of a realistic industrial option can be played by dual-fuel LNG motorisation, which combines the use of an energy source that is easily obtainable in adequate amounts, and already has transportation and distribution facilities. As previously stated, LNG delivers lower carbon dioxide emissions, with a more notable reduction made possible with the addition of biomethane. This is a significant benefit in the fight against climate change, which demands not only becoming carbon free by the year 2050, but also cutting emissions immediately to guarantee that overall emissions are as minimal as possible by that year. In the course of time, e-methane might take the role of LNG in these ships in an effort to help us reach our 2050 goal of becoming carbon-free. Even hydrogen and carbon dioxide acquired aboard ships might be used to create this e-methane (e-LNG) (Figure 1).

LNG is often less costly than HFO, but MDO costs about half as much, although nowadays (2022) due to the energy crisis these prices are constantly changing [20].

This article aims to investigate whether LNG can play the role of the transitional fuel towards our objective, which is the abolition of conventional fuels (HFO-MDO). It is fundamental to examine the emissions produced by the use of LNG in comparison with traditional fuels, and therefore, the new factor rE_{if} has to be introduced (as an emission reduction factor) in order to contribute to the analysis and evaluation of the environmental impacts. The coefficient rE_{if} values provide the necessary guidance for reducing emissions. As a case study to clarify the application of the $\mathrm{rE_{if}}$ coefficient, the port of Heraklion was selected. The Port Authority, the Lloyd's Register Fairplay (LRF) Sea Web database, and literature reviews provided all the information required [25]. Data processing employs the bottom-up approach. To calculate the overall cruise emissions from berthing ships in the port, as well as vessels using routes in the surrounding area, a zone of 10 km from the port of Heraklion was analysed [12]. This study was conducted based on the utilisation of various fuels in several vessel types. This research considers the hypothesis that the transition from conventional fuels to LNG should be implemented worldwide, meaning that all vessels should start using LNG. Comparative analysis was performed on the emissions from several case studies. Since Heraklion is one of Greece's most significant ports, it was chosen to be studied. On Crete's north shore, Heraklion lies about 80 km east of Rethymnon, 145 km east of Chania and its International Airport "Ioannis Daskalogiannis", and 3 km west of International Airport "Nikos Kazantzakis". Furthermore, the examined port is included among the busiest Greek ports. It is not only serving a heavily populated island (it is included in the top five in the Mediterranean Sea), but it is also the principal port of a stunning and popular vacation spot. It is estimated that the number of visitors per year is about 2 million. Therefore, numerous ships of different sizes and purposes travel to and from Crete.

The literature review is included in Section 1 of this study. The research approach is described in Section 2 of the article. Section 3 presents the outcome of the case study research. Finally, Section 4 sums up results and recommendations for further study.

2. rE_{if} Calculation Methodology

According to the Section 1, LNG is among the most potential substitute fuels in shipping, and its comparison with conventional fuels (HFO,MDO) leads to environmental profit. As part of this research, an activity-based marine emission inventory is developed. The emissions from the primary and auxiliary engines are estimated using the following general Equation (1), for each call [21,26,27]:

$$E_{i,f} = \sum\nolimits_{j,k} (A_j \times P_k \times LF_{j,k} \times EF_{i,f}) \quad (1)$$

E indicates the total amount of ship emissions (tons); *i* marks the kind of emission (CO_2, SO_2, NO_X, CO, CH_4, or $PM_{2.5}$); *f* specifies the type of fuel (conventional (c) or alternative (a) fuels); *j* indicates the operating phase of the vessel (i.e., sailing, moving–manoeuvring, or hotelling); *k* denotes the engine type (main (ME) or auxiliary (AE)); *P* engine power (kW) for the main engine P_{ME} and the auxiliary engine P_{AE}; *LF* engine load factor for the main engine LF_{ME} and the auxiliary engine LF_{AE}; *A* ship activity (h) (cruising–manoeuvring–hotelling); EFf: emission factor for conventional (c) and alternative (a) fuels (g/kWh).

The schematic figure in Figure 2 illustrates the emission-estimating procedure used in this study.

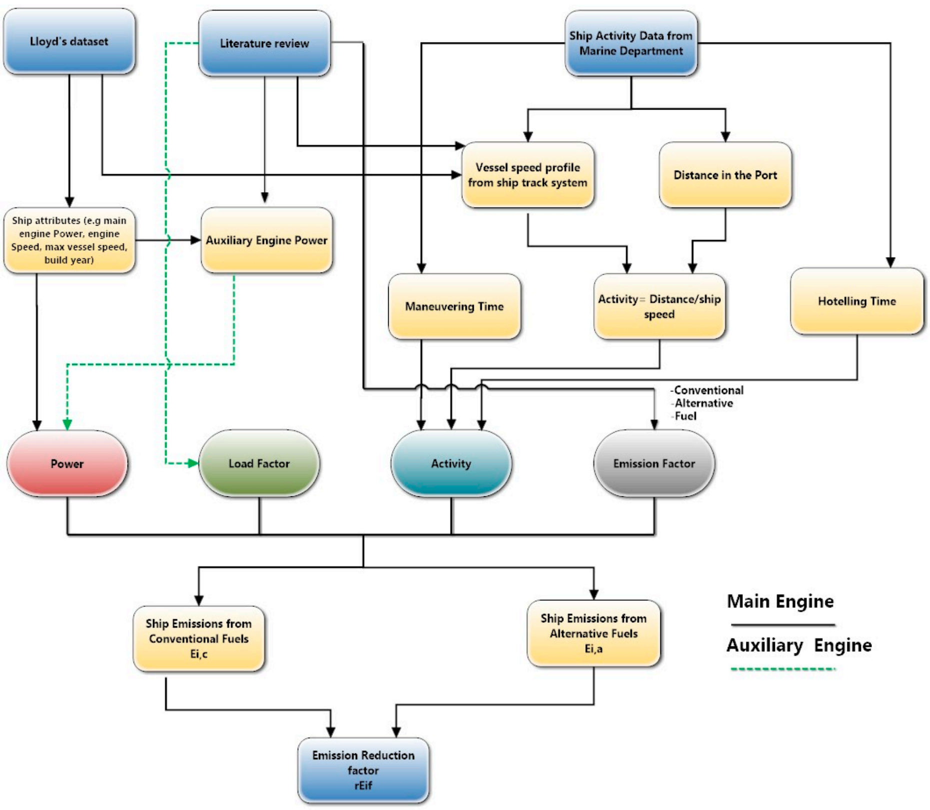


Figure 2. The ship emission assessment schematic diagram.

The engine load factor is the total power used by the engine while running in a particular operation (LF). A is the amount of time spent in each of the ship's operating modes while sailing (hrs). $A_C = D/U$, for the cruising mode, where D denotes the ship's travelled distance at sea up to 10 km (km) from the Heraklion Port [2,28]. This specialised method of operation examines just the routes taken by ships that arrived and exited the port under examination. The ship's velocity is indicated by the letter U. A_M is the average time spent manoeuvring (h) and A_H denotes the average time spent at berth (h) [27]. As indicated in the data, average load factors for main and auxiliary engines are calculated for each ship's activity mode (navigation, manoeuvring, and hotelling) in the Mediterranean port of Heraklion, and are shown in Table 1 [29–31].

Table 1. Engine load factors for ship activities within the port of Heraklion.

Activity	Cruise Ships		Coastal Passenger Ships		Other Ships	
	ME	**AE**	**ME**	**AE**	**ME**	**AE**
Cruising	0.80	0.75	0.80	0.75	0.80	0.75
Manoeuvring	0.20	0.75	0.20	0.75	0.40	0.75
At berth	0.00	0.60	0.00	0.45	0.00	0.75

The emissions factor (g/kWh) is estimated using detailed ship data, including engine type (main and auxiliary) and fuel type (conventional and alternative fuels), although it is not always precise [32,33]. All necessary data, such as ship manoeuvring–hotelling periods, calls in Heraklion Port in 2019, vessel names, dates, and call duration (time between departure and arrival), are meticulously gathered from local port authorities. The average installed main engine power (by ship, engine type, and size class), as well as the distribution of two-stroke and four-stroke engines, are calculated using the Lloyd's Register Fairplay (LRF) Sea Web database [25]. A recent study [34,35] determined the power of auxiliary machinery on cruise ships using the IMO energy efficiency design index (Table 2) [36], whereas for other types of ships, the power of auxiliary machinery is adopted from [12,28].

Table 2. Maximum continuous rating for diverse ship engines (kW) [2,24,26,28].

$\mathbf{MCR_{main\ engine}}$	>10,000 KW	<10,000 KW
$\mathbf{Power_{auxiliaryengine}}$	$=(0.025 \times \mathrm{MCR_{main\ engine}}) + 250$	$0.05 \times \mathrm{MCR_{main\ engine}}$

The principal categories of ships approaching Heraklion Port under study are Ro-Pax (roll-on/roll-off passenger), cruise ships, following the vehicle ships, and general cargo. Table 3 summarises traffic data of the port for the year 2019 [33]. The dominant type of vessel at Heraklion Port is Ro-Pax. Despite their modest size, cruise ships, as well as other kinds of ships, will play a significant role in the ultimate outcome.

Table 3. Traffic statistics in the port of Heraklion for the year 2019.

Ships Categories	Ships Calls
Cruise Ships	204
Ro Pax	1462
Container Ships	51
Vehicle Carriers	12
General Cargo	89

From the port's perspective, the change in emissions caused by the substitution of conventional (c) with alternative fuels (α), $\Delta E_{i,f}$, can be calculated using Equation (2).

$$\Delta EF_{i,f} = E_{i,c} - E_{i,a} = \sum_{j,k} P_k \times LF_{j,k} \times A_j \times (EF_{i,c} - EF_{i,a}) \tag{2}$$

It is possible to determine the percentage of emission reduction near ports as a result of a specific policy by considering the baseline scenario, which includes all stages of activities for all ships approaching the port. The emission reduction factor rE_{if} is used to express this estimate, as illustrated in Equation (3):

$$rEif = \frac{\Delta Eif}{Eic} \times 100 \tag{3}$$

ΔEif represents the emission savings achieved via the chosen fuel change strategy in the three activities (cruising–manoeuvring–hotelling) by ship type, and Eic is the total emissions generated by all ships calling at the port using conventional fuel.

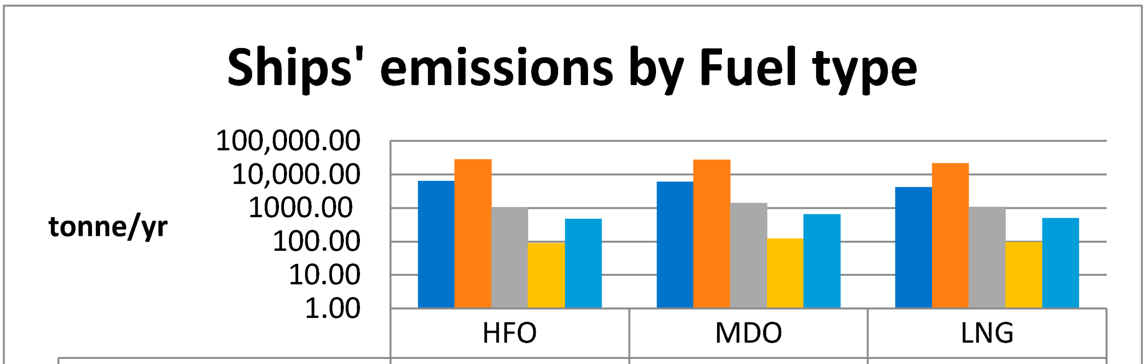
3. Results and Discussion

In this study, marine emissions are quantified using the output of the activity-based emission model. The total shipping pollution for the year 2019 in the port of Heraklion is shown in Table 4. It sums the total emissions produced by ships of every category during all kinds of operating modes, using either conventional (HFO-MDO), or alternative (LNG) fuels.

Table 4. Amounts of estimated emissions (tn/year) by pollutant category and fuel type (results by author).

	Emissions (tn/yr)		
	Conventional Fuels		Alternative Fuels
	HFO	MDO	LNG
CO_2	34,915.53	34,194.31	27,113.04
NO_x	807.45	858.73	140.47
CO	38.54	30.63	89.02
PM	37.95	9.87	0.37
SO_2	343.51	34.85	0.35
CH_4	0.56	0.57	318.68
Total	36,173.60	35,159.02	27,670.96

Figure 3 demonstrates that regardless the type of fuel used, cruise ships and Ro-Pax ships account for the overwhelming majority of vessel emissions in the port of Heraklion. Due to the popularity of this port as a touristic destination on an international scale, Ro-Pax and cruise ships are the most pollution contributors. CO_2 is the highest pollutant, followed by NOx, and SO_2 is the third most prevalent pollutant in conventional fuels. On the other hand, in alternative fuels there is a difference in emissions, since sulphur dioxide emissions are almost zero, as seen in Table 4.



	HFO	MDO	LNG
Cruise Ships	6386.75	6099.02	4215.16
Ro-Pax	28,282.10	27,008.10	21,735.69
Container Ships	1023.49	1396.28	1065.59
Vehicle Carriers	89.04	121.51	97.81
General Cargo Vessels	480.70	655.62	500.32

Figure 3. Amounts of emissions (tonne/year) by ship category and fuel type.

Table A1 (see Appendix A) shows differences in emissions due to fuel change. It should be emphasised that this study estimates emissions from cruising, manoeuvring, and berthing for each ship type. The negative sign on CO and CH_4 pollutants indicates the increase in these pollutants when the ship uses LNG.

As illustrated in Figures 6 and 7, the emissions reductions calculated using the rE_{iHFO} and rE_{iMDO} coefficient, respectively, demonstrate unequivocally that switching from conventional (HFO-MDO) to alternative fuels (LNG) results in lower SO_2, CO_2, and NO_x emissions, but higher CO and CH_4 emissions. The value of the coefficient rE_{CH4f} is too large to fit in scale in Figure 4. In comparison with other emissions, CO and CH_4 emissions from dual-fuel engines are often greater than those from traditional engines running on diesel. Engine load affects emissions, since low engine loads produce greater emissions. The combination of lower engine loads and low temperatures in the cylinder, along with a low concentration of oxygen in the mixture and a quick response time, boosts CO generation (2010) [37]. Additionally, as shown in Figure 5, in manoeuvring mode there is a slight change in emissions, while in cruising and hotelling modes there is a significant change in emitted pollutants.

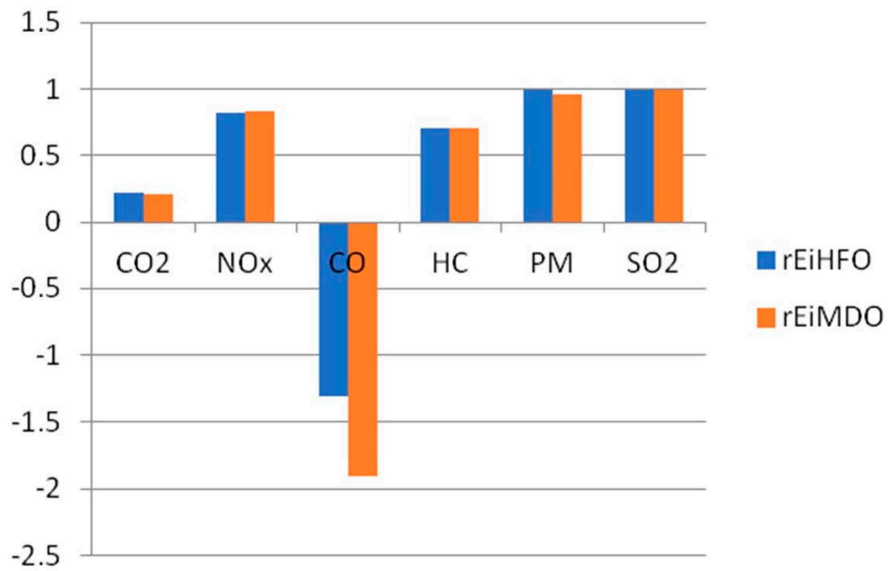


Figure 4. The rE_{iHFO} and rE_{iMDO} coefficient for each pollutant category.

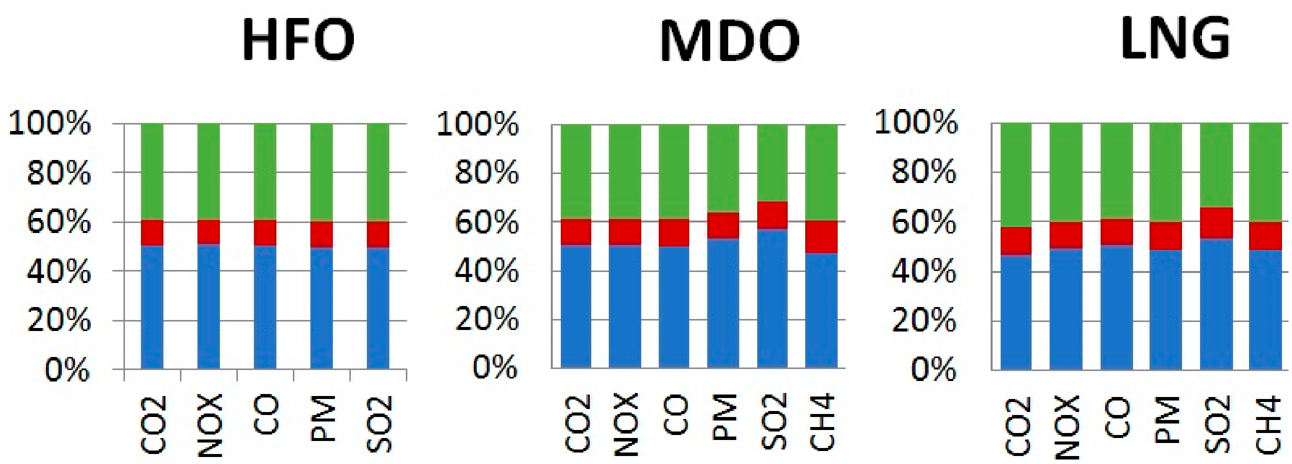


Figure 5. Total exhaust emissions during ship operational modes (cruising (blue colour)–manoeuvring (green colour)–hotelling (red colour)) per fuel type.

The emission reduction Factor rE_{if}, which quantifies the reduction in emissions associated with the use of LNG as a substitute for traditional HFO, is shown in Figure 6 for each pollutant and ship activity: rE_{CO2HFO} for CO_2 demonstrates the decrease in CO_2 emissions when LNG is used as an alternate fuel in all types of ships and all types of operations. Cruise ships and containers exhibit the greatest percentage decrease in CO_2 emissions during the cruising period, whereas the reduction rate is almost consistent for the other two phases and all kinds of ships (and over 22%). The greatest decrease in rE_{NOxHFO} occurs when LNG is used as an alternative fuel for all types of ships and operating phases, at a rate of more than 82 percent. While rE_{PMHFO} and rE_{SO2HFO} exhibit the greatest reductions, utilising liquified natural gas as an alternate fuel reduces emissions by more than 100% for all types of ships and operating phases. In contrast to the aforementioned pollutants, the rE_{if} coefficients for CO and CH_4 pollutants are negative, indicating a rise in pollutants when LNG is used as an alternative fuel, as shown in Figure 7.

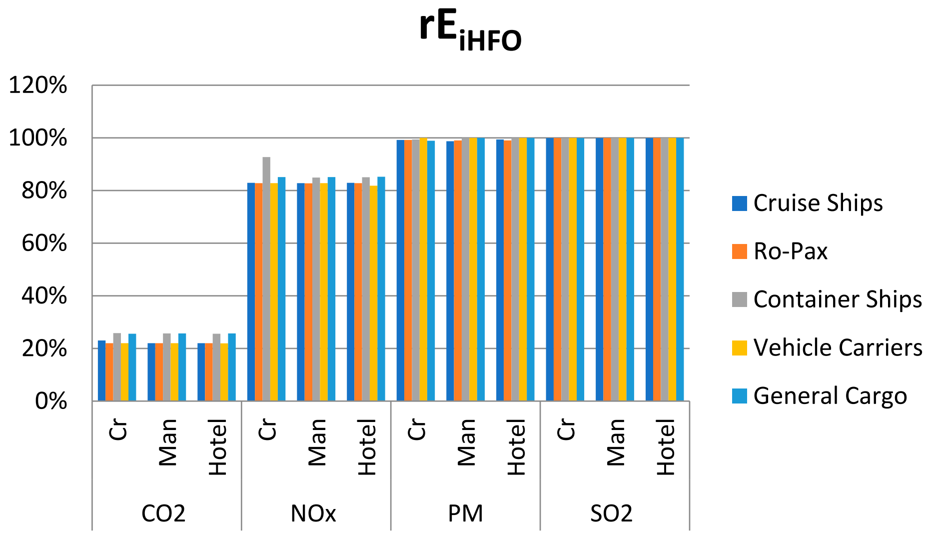
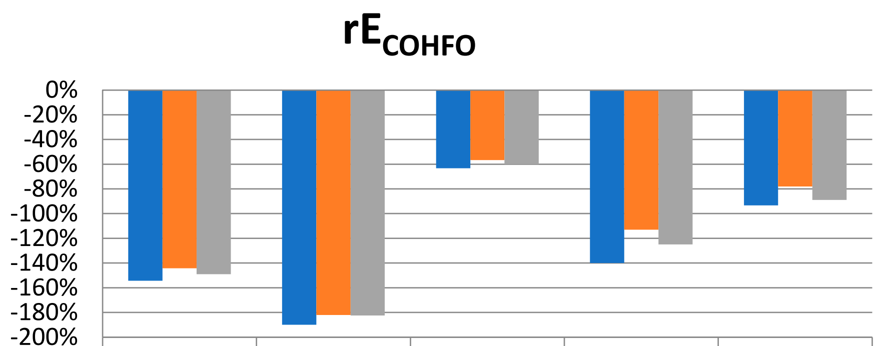


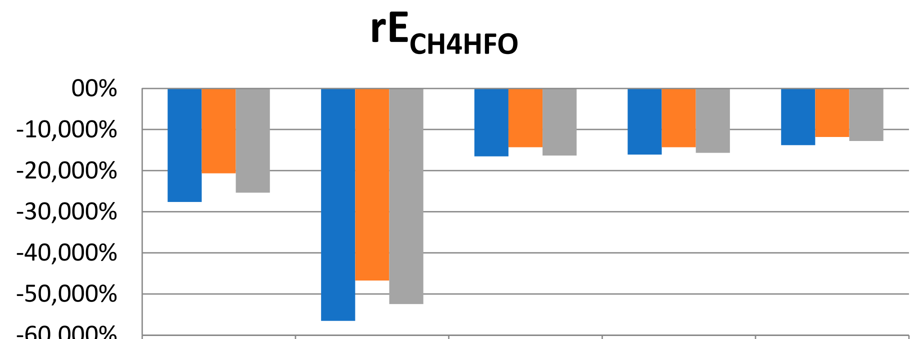
Figure 6. Emission reduction factor (rE_{CO2HFO}, rE_{NOXHFO}, rE_{SO2HFO}, rE_{PMHFO}) using alternative LNG fuel to conventional HFO fuel for all categories of vessels and their 3 activities (cruising–manoeuvring–hotelling).



	Cruise Ships	Ro-Pax	Container Ships	Vehicle Carriers	General Cargo
CO Cr	-154%	-190%	-63%	-140%	-93%
CO Man	-144%	-182%	-57%	-113%	-78%
CO Hotel	-149%	-183%	-60%	-125%	-89%

(**a**)

Figure 7. *Cont.*



	Cruise Ships	Ro-Pax	Container Ships	Vehicle Carriers	General Cargo
CH4 Cr	-27,630%	-56,513%	-16,513%	-16,100%	-13,780%
CH4 Man	-20,634%	-46,730%	-14,320%	-14,300%	-11,800%
CH4 Hotel	-25,360%	-52,454%	-16,320%	-15,680%	-12,780%

(**b**)

Figure 7. Emission reduction factor (**a**) rE$_{COHFO}$, (**b**) rE$_{CH4HFO}$ using alternative LNG fuel to conventional HFO fuel for all categories of vessels and their 3 activities (cruising–manoeuvring–hotelling).

When MDO is used as the traditional propellant and LNG is used as the alternative fuel, the rE$_{iMDO}$ emission reduction factor behaves similarly to that illustrated in Figures 8 and 9.

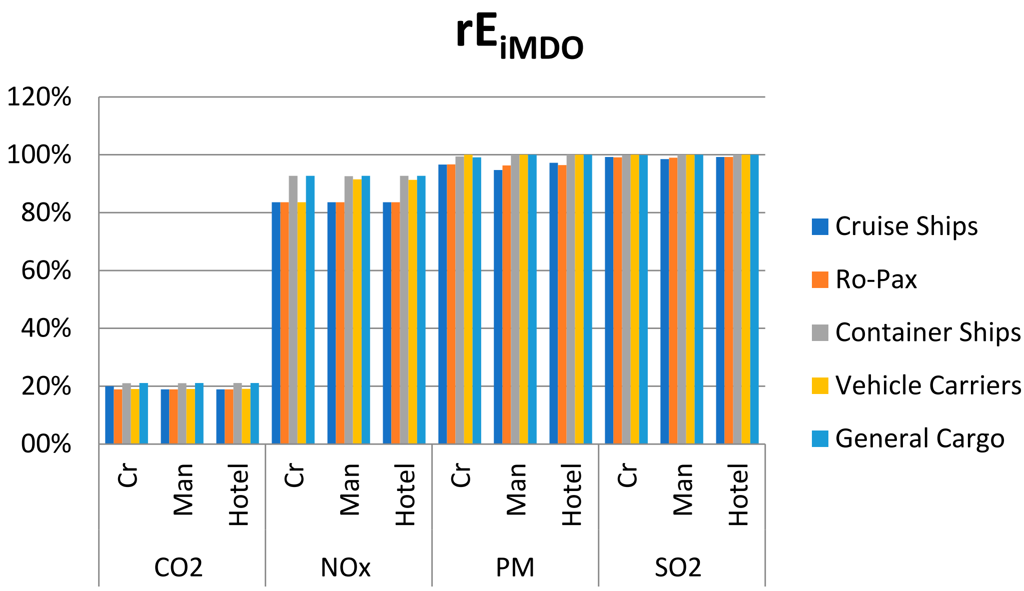
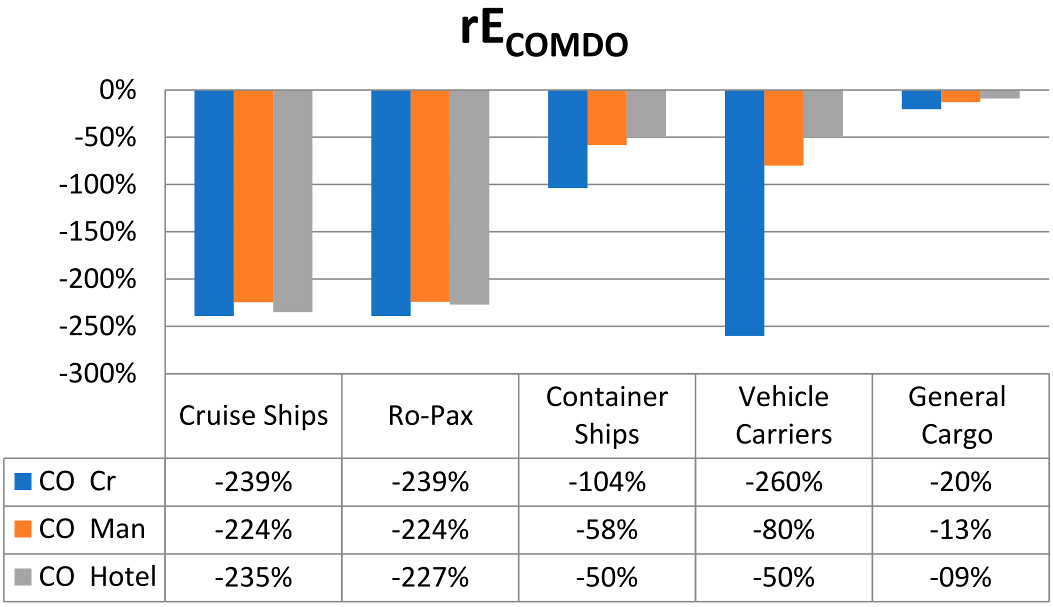
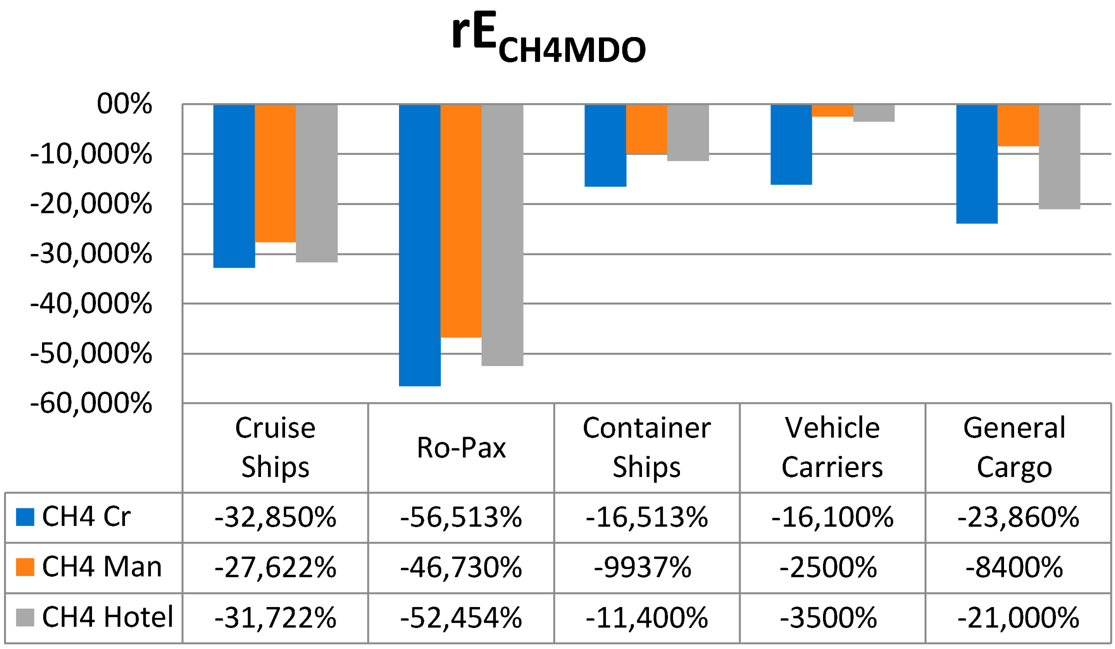


Figure 8. Emission reduction factor (rE$_{CO2MDO}$, rE$_{NOXMDO}$, rE$_{SO2MDO}$, rE$_{PMMDO}$) using alternative LNG fuel to conventional MDO fuel for all categories of vessels and their 3 activities (cruising–manoeuvring–hotelling).



	Cruise Ships	Ro-Pax	Container Ships	Vehicle Carriers	General Cargo
CO Cr	-239%	-239%	-104%	-260%	-20%
CO Man	-224%	-224%	-58%	-80%	-13%
CO Hotel	-235%	-227%	-50%	-50%	-09%

(**a**)



	Cruise Ships	Ro-Pax	Container Ships	Vehicle Carriers	General Cargo
CH4 Cr	-32,850%	-56,513%	-16,513%	-16,100%	-23,860%
CH4 Man	-27,622%	-46,730%	-9937%	-2500%	-8400%
CH4 Hotel	-31,722%	-52,454%	-11,400%	-3500%	-21,000%

(**b**)

Figure 9. Emission reduction factor (**a**) rE_{COMDO}, (**b**) rE_{CH4MDO} using alternative LNG fuel to conventional MDO fuel for all categories of vessels and their 3 activities (cruising–manoeuvring–hotelling).

4. Conclusions

The most widespread option to replace MDO and HFO in maritime is an alternative fuel such as LNG, which could decrease emissions of CO_2 while conforming to SO_x and NO_x emission limits in a cost-effective way. Methane slip, on the other hand, decreases the greenhouse gas (GHG) benefit, with a drastic drop of 8–20 percent in comparison with HFO and MDO. LNG is now less expensive than existing maritime fuels, despite the energy crisis nowadays (2022), but infrastructure needs to be upgraded to face competition. LNG is a transitional fuel from oil to electricity and carbon-free fuels. The maritime fuel mix will change dramatically.

Additionally, this study utilises a bottom-up technique based on in-port operations to measure SO_2, NO_x, CO_2, CO, CH_4, and PM emissions from ships entering Heraklion Port in

2019, resulting in a unique emissions inventory addressing the problem of ship-generated air pollution. Through the emission reduction factor, rE_{if}, this study compares pollutants produced by conventional and alternative fuels. The research focuses on the environmental consequences of ports (because of their closeness to areas with high population) and offers statistic elements for Heraklion Port, which is the third most popular port in Greece, for the year 2019. During this year, emissions from ships operating on conventional fuels are 34,915.53 tons CO_2, 807.45 tons NOx, 343.51 tons SO_2, 38.54 tons CO, 37.95 tons PM, and 0.56 tons CH_4. The contaminants listed above are associated with ordinary HFO fuel. When MDO is used as a fuel, the following pollutants are emitted: CO_2 emissions total 34,194.31 tons, NO_x emissions total 858.73 tons, SO_2 emissions total 34.85 tons, CO emissions total 30.63 tons, PM emissions total 9.87 tons, and CH_4 emissions total 0.57 tons. When an emission reduction strategy is applied by switching from conventional to alternative LNG fuel, the following emissions are calculated: 27,113.04 tonnes CO_2, 140.47 tonnes NO_x, 0.35 tonnes SO_2, 89.02 tonnes CO, and 0.37 tonnes PM, 318.68 tonnes CH_4. The majority of emissions are produced by Ro Pax ships, while cruise ships follow. The maximum percentage of all pollutants is determined during sailing. The emission reduction factor, rE_{if}, for the conventional HFO fuel is presented as follows: rE_{CO2HFO} 22.35%, rE_{NOxHFO} 82.60%, rECOHFO −130.98%, rE_{PMHFO} 99.03%, rE_{SO2HFO} 99.90%, rE_{CH4HFO} −56807.14%, rE_{CO2MDO} 20.71%, $rENO_{xMDO}$ 83.64%, rE_{COMDO} −190.63%, rE_{PMMDO} 96.25%, rE_{SO2HFO} 99.00%, and rE_{CH4MDO} −55808.77%. According to the rE_{if} coefficient, switching from conventional to alternative fuel contributes to a major reduction in SO_2, NO_x, and PM pollutants, and a less significant decrease in CO_2 pollutants, while rE_{if} values for CO and CH_4 pollutants are negative, indicating that there are increased emissions for CO and CH_4 due to methane slip. This research considers only main and auxiliary engines; emissions from other equipment are not included. Additional equipment data may be gathered for subsequent experiments, resulting in more precise findings.

Furthermore, it is unnegotiable that ship emissions should be minimised. Transition from conventional to alternative fuels during cruising and manoeuvring leads to a substantial decrease in major pollutants and is therefore suggested as a solution. Furthermore, for the hotelling mode, the reduction in emissions is not equivalent to manoeuvring and cruising modes; thus, other methods (such as electricity provided by shore) should be researched as a better solution.

Finally, it is clear that decarbonisation can be achieved through the reduction of maritime pollution, the use of combined fuels, and innovative technologies and strategies in different ways, responding to both short- and long-term solutions. The study proves that the use of LNG leads to a decrease in certain emissions, and considering that it is cost-effective, operationally secure, and already widely adopted by ship-owners, makes LNG the best choice among transitional fuels. Until the point of adequate research and infrastructure for the use of hydrogen that is both nuclear and renewable, LNG will provide immediate environmental benefits.

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Appendix A

Table A1. Emission difference by fuel type, ship category, and activity (cruising (Cr)–manoeuvring (Man)–hotelling (Hotel)) within 5,40NM from the port.

	ΔE_{ifMDO}																	
Ship Type		**CO_2**			**NO_x**			**CO**			**PM**			**SO_2**			**CH_4**	
	Cr	**Man**	**Hotel**	**Cr**	**Man**	**Hotel**	**Cr**	**Man**	**Hotel**	**Cr**	**Man**	**Hotel**	**Cr**	**Man**	**Hotel**	**Cr**	**Man**	**Hotel**
Cruise Ships	823.3	216.43	718.02	20.77	24.01	79.7	−2.14	−2.14	−5.44	0.29	0.31	1.04	1.02	1.16	3.84	−9.38	−10.85	−36.05
Ro-Pax	974.3	1794.02	2197.53	108.19	199.13	244.01	−10.96	−17.84	−16.67	1.46	2.63	3.21	5.26	9.5	11.69	−48.83	−90.06	−110.38
Container Ships	422.4	867.35	430.22	15.19	31.2	15.48	−0.49	−0.2	0	0.47	0.97	0.47	3.74	7.69	3.81	−1.89	−3.91	−1.94
Vehicle Carriers	4.07	49.03	69.66	0.45	1.79	2.55	−0.05	−0.04	−0.02	0.01	0.06	0.08	0.02	0.45	0.64	−0.19	−0.37	−0.53
General Cargo	154.3	187.6	465.89	5.55	6.75	16.76	−0.03	−0.04	−0.1	0.17	0.22	0.53	1.37	1.66	4.13	−0.01	−0.84	−2.1
Total	2378	3114.43	3881.32	150.15	262.88	358.5	−13.67	−20.26	−22.23	2.4	4.19	5.33	11.41	20.46	24.11	−60.3	−106.03	−151
	ΔE_{ifHFO}																	
Ship Type		**CO_2**			**NO_x**			**CO**			**PM**			**SO_2**			**CH_4**	
	Cr	**Man**	**Hotel**	**Cr**	**Man**	**Hotel**	**Cr**	**Man**	**Hotel**	**Cr**	**Man**	**Hotel**	**Cr**	**Man**	**Hotel**	**Cr**	**Man**	**Hotel**
Cruise Ships	862.17	261.39	867.2	19.69	22.79	75.62	−1.88	−1.85	−4.48	1.1	1.27	4.24	10.1	11.71	38.78	−9.38	−10.81	−36.1
Ro-Pax	1176.7	2166.6	2654.26	102.6	188.89	231.44	−9.79	−15.35	−13.75	5.8	10.52	13.01	52.6	96.93	118.71	−48.8	−90.2	−109.71
Container Ships	422.36	182.54	90.54	15.19	14	6.95	−0.1	−0.81	−0.31	0.5	0.77	0.37	3.74	6.99	3.46	−1.89	−3.92	−1.94
Vehicle Carriers	4.91	9.07	12.95	0.43	0.79	1.13	−0.04	−0.08	−0.07	0.02	0.05	0.06	0.22	0.41	0.58	−0.19	−0.37	−0.53
Cargo	32.46	39.62	98.05	2.49	3.03	7.52	−0.14	−0.17	−0.43	0.1	0.18	0.42	1.25	1.51	3.76	−0.02	−0.84	−2.1
Total	2498.6	2659.3	3723	140.43	229.5	322.66	−11.9	−18.26	−19.04	7.6	12.79	18.1	67.96	117.55	165.29	−60.31	−106.14	−151.23

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