

Impact study of the fuel type used on the energy efficiency costs values and harmful emissions generation for small, medium and large container vessels

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Abstract. Annually a large amount of goods has been transported over the world and the most of the transportation is carried by seaborne. Although the seaborne trade is considered to be the most efficient – economically and environmentally friendly way of transportation an enormous amount of fossil fuels is used to fulfil the operation of the merchant fleet. Although we are living in times where efforts are directed to improvement of the state of the environment and reduction of the negative impact of the Greenhouse Gases, the fossil fuels still remain the main energy source used to run the internal combustion engines widely used in the ships nowadays. A well-known fact is that the fuel burning leads to significant harmful emissions generation causing a serious negative effect on the surrounding us environment. The introduced by IMO and MEPC requirements regarding the Greenhouse Gases (GHG) imposes for development and application of new criteria when selecting the ship's propulsion plant. In the current article will be observed three ship groups consisting of real container vessels. The purpose is to analyse the impact caused by the fuel type used in the ship's engines on the GHG generation and the economic indicators related with fuel costs

1 Introduction

The seaborne trade is a constantly evolving area developing and incorporating new technologies with purpose to turn the shipping into one much cleaner and environmentally friendly industry.

Annually the worldwide shipping uses a large amount of fossil fuels to run the available fleet, which burning in the ship engines is resulting in enormous GHG generation negatively reflecting on the surrounding us environment.

The GHG emissions — including carbon dioxide (CO₂), methane (CH₄) and nitrous oxide (N₂O), expressed in CO₂e — of total shipping have increased from 977 million tonnes in 2012 to 1,076 million tonnes in 2018 (9.6% increase). In 2012, 962 million tonnes were CO₂ emissions, while in 2018 this amount grew 9.3% to 1,056 million tonnes of CO₂ emissions. The share of shipping emissions in global anthropogenic emissions has increased from 2.76% in 2012 to 2.89% in 2018 [1].

The values for global CO₂ emissions and the share that falls for the shipping industry in the period of 2012÷2018 are given in Table 1 (*units are in million tonnes*).

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Table 1. Total Global and Shipping CO₂ Emissions (*Source – IMO GHG Study 2020*)

Year	Global CO ₂ Emissions	Shipping CO ₂ Emissions	Shipping as percentage of global
2012	34 793	962	2.76
2013	34 959	957	2.74
2014	35 225	964	2.74
2015	35 239	991	2.81
2016	35 380	1 026	2.90
2017	35 810	1 064	2.97
2018	36 573	1 056	2.89

With the development of the modern engine building there is a real opportunity to equip the newbuilding ships or to retrofit the existing fleet (if possible) with new more efficient engines, using fuels which differ from the conventional ones widely used in the shipping nowadays. It is important to note that the modern engines are characterized with lower specific fuel consumption (SFC) when compared to the previous generations. This leads to fuel costs reduction for each separate voyage as well as for each operational period of the ship.

The mentioned fact has two really important aspects for the ship's operation:

- First one could be considered as purely economic – reducing the operational costs related to the fuel, which constitutes a main part from the total expenditures.
- The second one is related to the regulations from harmful emissions generated by shipping, which at the present moment are very strict. Therefore, when taking a decision regarding the main engine type selection it is mandatory to account not only the technical and economic indicators, but the ecological ones as well.

With purpose to reduce the volume of GHG and to improve the state of the environment, the International Maritime Organization (IMO) and Marine Environment Protection Committee (MEPC) established some requirements in connection with the GHG generated by the shipping industry.

In 2011, IMO adopted mandatory technical and operational energy efficiency measures which are expected to significantly reduce the amount of CO₂ emissions from international shipping. These mandatory measures (EEDI/SEEMP) entered into force on 1 January 2013. IMO has adopted important guidelines aimed at supporting implementation of the mandatory measures to increase energy efficiency and reduce GHG emissions from international shipping [2].

In 2018, IMO adopted an initial strategy on the reduction of GHG emissions from ships, setting out a vision which confirms IMO's commitment to reducing GHG emissions from international shipping and to phasing them out as soon as possible [3].

In order to comply with the requirements, set out by the organizations, the ship engine manufacturers developed much more efficient engine types, able to operate with gaseous and conventional fuels, or a combination of them. Increasingly wider applications are finding the so-called Dual-Fuel Engines, which are able to operate with gaseous fuels as LNG and a small portion of diesel oil used as a pilot fuel.

One of the advantages with gas-fuelled vessels is the ability to adjust operation when the fuel prices rise and modern exhaust-emission limits tighten. Indeed, service experience shows that the dual-fuel engine delivers significant reductions in CO₂, NO_x and SO_x emissions [4].

Three ship classes accounted for 55% of the total shipping CO₂ emissions: container ships (23%), bulk carriers (19%), and oil tankers (13%). These three ship classes also accounted for 84% of total shipping transport supply (deadweight tonne nautical miles, or dwt-nm) [5].

In Figure 1 are depicted the CO₂ emissions generation depending on the ship's class (Source – [5]).

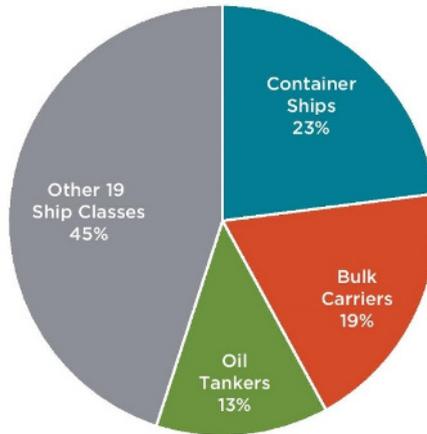


Fig. 1. Shares of CO₂ emissions by ship's class

In the current article will be observed three types of container vessels – Feeder, Post-Panamax, and ULCV which could be classified respectively as small, medium and large ships.

The aim set out in the current article is to analyse the possibilities for utilizing the dual-fuel technology in the composition of the ship power plants and to account the benefits following due to such an intervention. With the calculation performed in the current paper we aim to help for the facilitation in connection with the ship power plant selection.

With purpose to perform that we will use as example existing ships and a substitution of their power plants will be done with regard to account the improvement in GHG emitting only due to the proper engine selection.

2 Dual-Fuel technology

Today, ship propulsion is not just about successful movement of the ship in the water. It also includes using the best mode of propulsion to ensure a better safety standard for the marine ecosystem along with cost efficiency [6].

Nowadays a wide range of options intended for the ship propulsion are available. The typical arrangement includes two stroke diesel engines as a prime mover and a number of electric generators propelled by diesel engines ensuring the electrical production

With the stricter requirements introduced by IMO and MEPC regarding the energy efficiency of the ships and the GHG emitting, the shipping industry had been forced to act in direction leading to efficiency improvement of the components used in the ship's propelling systems.

In the past years the marine engine manufacturers introduced modern engines working on the dual-fuel principle able to operate with fuels different from the well-known

conventional fuels like HFO, MDO and MGO. These engines are able to operate with gaseous fuels like LNG which are considered much cleaner than the conventional ones.

Essentially, the dual-fuel engines don't differ from the well-known diesel engines widely spread in the shipping industry. Like the diesel engines they also provide a wide range of power and speeds ensuring the possibility to propel each ship class available.

There are two main engines concepts for LNG: high and low-pressure. In the high-pressure dual-fuel LNG concept, the LNG is injected under high pressure and ignited by a small quantity of diesel. This produces virtually complete combustion of the gas, and thus virtually no un-combusted methane. In the low-pressure system, the LNG is injected under low pressure and ignited by a small amount of diesel. This produces low NO_x emissions that meet IMO Tier III, the strictest NO_x requirements, while high-pressure LNG requires additional abatement technologies to satisfy IMO Tier III [7].

The main pros when using dual-fuel engines is the opportunity to run the engines with much cleaner fuel like LNG which almost fully eliminate the sulphur oxides (SO_x) and Particulate Matter (PM), and also substantially reduce the nitrous oxides (NO_x) generated due to the fuel burning in the marine engines.

The common arrangement of the container ships propulsion system consists of a Main Engine (ME) and Diesel Generators (DG), usually one ME and up to 3 DG are involved.

On Figure 2 is shown the typical arrangement commonly used in the container ship propulsion systems.

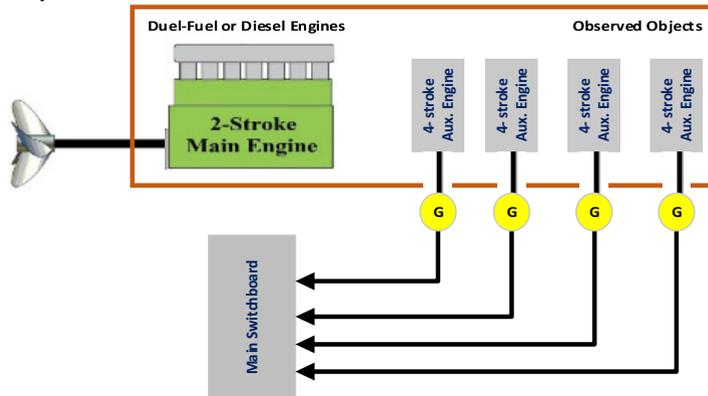


Fig. 2. Typical container ship propulsion system arrangement

3 Study scenario and calculation methodology

In the current paper will be observed 3 types of container vessels – small, medium and large respectively. To account the benefits achieved by the dual-fuel propulsion, calculations will be performed first for the initial equipped propulsion systems of each ship, and then for the alternative modern propulsion systems.

For the purpose of current article, we have chosen real container vessels of MSC company, which is one of the biggest companies in the field of container seaborne trade. The initial data necessary for the purpose of the calculations and for the size of the ships are presented in Table 2, more detailed information regarding the chosen ships could be found in [8].

Table 2. Initial data for small, medium and large container vessels

MSC AMY	
ME	MAN B&W, 6L70MC, 16 980 kW at 108 rpm
DG	MAN B&W, 4 x 6L23/30H, 1050 kW each
TEU	1 683
Deadweight	22 308 t
Speed	Max 20.5 knots
MSC ATHENS	
ME	MAN B&W, 9SME-C8.2, 47 430 kW at 78 rpm
DG	MAN B&W, 2 x 8L32/40 – 4000 kW each, 2 x 9L32/40 – 4500 kW each
TEU	8 827
Deadweight	95 380 t
Speed	Max 22.0 knots
MSC HAMBURG	
ME	MAN B&W, 11S90ME-C9, 59 780kW at 82 rpm
DG	MAN B&W, 4 x 9L32/40, 4500 kW each
TEU	16 652
Deadweight	184 100 t
Speed	Max 23.0 knots

With regard to fulfil the goals set, we substitute the main components of the propulsion system (ME and DG) of each considered ship with alternative modern engines with equivalent power working on the Dual-Fuel principle. The rest of the ship's parameters remain unchanged.

In Table 3 are shown the chosen alternative options for each observed ship.

Table 3. Alternative propulsion options for small, medium and large container vessels

MSC AMY	
ME	MAN B&W, 7G60ME-C10.5-GI, 16 980 kW at 98 rpm
DG	MAN B&W, 4 x 8L23/30DF, 1000 kW each
MSC ATHENS	
ME	MAN B&W, 9G90ME-C10.5-GI, 47 430 kW at 78 rpm
DG	MAN B&W, 2 x 8L35/44DF + 2 x 9L35/44DF, 4080 kW + 4590 kW each
MSC HAMBURG	
ME	MAN B&W, 11G95ME-C10.5-GI, 59 780 kW at 82 rpm
DG	MAN B&W, 4 x 9L35/44DF, 4590 kW each

Energy Costs Calculation

Amongst the most important parameters which each marine engine could be described with are its power, speed and specific fuel consumption (SFC).

The fuel consumption represents the basic value used to account the economy of each marine propulsion system.

The main power propulsion plant selection primarily affects the fuel/lubricating oil expenses and maintenance costs i.e., 57% of the operating cost [9]

To calculate the amount of fuel used for the observed period, the following formulas has been used:

$$FC_{(S)} = (\tau_S \times 24 \times P_{B(ME)} \times SFC_{ME}) \times 10^{-6} + (\tau_S \times 24 \times P_{B(AE)} \times SFC_{AE} \times \sum AE) \times 10^{-6} \quad (1)$$

Where:

$FC_{(S)}$ – total fuel consumption of the ship in sailing period, [tonnes];

τ_S – time spent at sea, [days];

$P_{B(ME)}$ – main engine power, [kW];

SFC_{ME} – main engine fuel consumption, [g/kWh];

$P_{B(AE)}$ – auxiliary engine power, [kW];

SFC_{AE} – auxiliary engine fuel consumption, [g/kWh].

$$FC_{(P)} = (\tau_P \times 24 \times P_{B(AE)} \times SFC_{AE} \times \sum AE) \times 10^{-6} \quad (2)$$

Where:

$FC_{(P)}$ – total fuel consumption at port stay, [tonnes];

τ_P – time spent at port, [days].

$$FC_{(T)} = FC_{(S)} + FC_{(P)} \quad (3)$$

Where:

$FC_{(T)}$ – total fuel consumption for the observed period, [tonnes].

With purpose to find the energy costs regarding the fuel type used for the observed in the current paper period, the following equation has been used:

$$EC = FC_{(T)} \times PR_{FO} \quad (4)$$

Where:

EC – energy costs [USD];

PR_{FO} – fuel price, [USD].

With purpose to the calculations performance, the following assumptions have been considered:

- ME power and SFOC at 75%;
- Diesel ME operates with HFO, Dual-Fuel ME operates with LNG and MDO as Pilot Fuel;
- DG power and SFOC at 50%.
- Diesel Generators operates with MDO, Dual-Fuel Generators operates with LNG and MDO as Pilot Fuel;
- ME in operation only when sailing;
- Number of DG in operation when sailing – 2 x 50% Power;
- Number of DG in operation at port stay – 2 x 50% Power;
- Observed period – 1 year;
- Time spent at sea – 80% or approximately 292 days;

- Time spent at port – 20% or approximately 73 days.

The calculations concerning the energy costs strictly depends on the fuel prices. The fuel prices vary depending on the sailing region and ports visited. For the purpose of our calculations will be considered the global average prices for the last six months (01.12.20÷31.05.21) for HFO and MDO based on [10], and the average prices for the same period for LNG at Henry Hub based on [11].

The information concerning the specific fuel oil consumption of the ME and DG is based on the relevant engines project guides and with the help of CEAS (Computerized Engine Application System) application provided for free use on the official website of the company MAN B&W.

In Table 4 are given the input data necessary for the calculations regarding the amount of fuel used and the energy costs for the observed period.

All of the values are according to the assumptions set earlier in the current paper.

Table 4. Input data necessary for the calculations of fuel consumption and energy costs for the observed ships

Ship	MSC AMY	MSC ATHENS	MSC HAMBURG
$P_{B(ME)}$, [kW] at (75%)	12735	35572.5	44835
SFC_{ME} (intl.), [g/kWh] at 75%	170.5 (HFO)	159.5 (HFO)	159.1 (HFO)
SFC_{ME} (alt.), [g/kWh] at 75%	128.2 (LNG) 3.34 (MDO)	126.9 (LNG) 3.36 (MDO)	121.5 (LNG) 3.70 (MDO)
$P_{B(AE)}$, [kW] at (50%)	525	2125	2250
SFC_{AE} (intl.), [g/kWh] at 50%	196.5 (MDO)	197.0 (MDO)	197.0 (MDO)
SFC_{AE} (alt.), [g/kWh] at 50 %	206.1 (LNG) 3.60 (MDO)	193.5 (LNG) 3.80 (MDO)	193.5 (LNG) 3.80 (MDO)
HFO Price [\$/tonne]	402.50		
MDO Price [\$/tonne]	577.50		
LNG Price [\$/tonne]	168.35		

Harmful Emissions Quantification

The FC and the energy costs arising from the former are only the one side of the coin. The other side is the ecology and the influence on the surrounding us environment rendered by the fuel burning in the internal combustion engines. The aim set in front of each shipping company and the shipping society at all is to reduce the harmful emissions generation and therefore the negative impact caused by them.

Quantification of the CO₂, NO_x, SO_x and PM are based on the fuel total fuel consumption calculated and the values for estimation the harmful emissions given in [8] and [9].

With purpose of the calculations performed, the following assumptions have been considered:

- HFO with sulfur content 3.5%;
- MDO with sulfur content 0.5% when sailing;
- MDO with sulfur content 0.1% at port stay;
- LNG Calorific Value – 48 000 kJ/kg;

- ME considered as slow-speed engine;
- AE considered as medium-speed engine.

With purpose to estimate the GHG emissions emitted by the observed ships for the period set, the following formulas has been used:

$$CO_2 = (FC_{(T,ME)} + FC_{(T,AE)}) \times E_{F(CO_2)} \quad (5)$$

Where:

CO₂ – carbon dioxide emissions, [t];

FC_(T,ME) – total FC of main engine, [t];

FC_(T,AE) – total FC of auxiliary engine, [t];

E_{F(CO₂)} – emission factor for CO₂ [kg/t fuel].

$$SO_x = (FC_{(T,ME)} + FC_{(T,AE)}) \times E_{F(SO_x)} \quad (6)$$

Where:

SO_x – sulfur oxides emissions, [t];

E_{F(SO_x)} – emission factor for SO_x [kg/t fuel].

$$NO_x = (FC_{(T,ME)} + FC_{(T,AE)}) \times E_{F(NO_x)} \quad (7)$$

Where:

NO_x – nitrogen oxides emissions, [t];

E_{F(NO_x)} – emission factor for NO_x [kg/t fuel].

$$PM = (FC_{(T,ME)} + FC_{(T,AE)}) \times E_{F(PM)} \quad (8)$$

Where:

PM – particulate matters emissions, [t];

E_{F(PM)} – emission factor for PM [kg/t fuel].

In Table 5 are given the emission factor values in necessary for GHG estimation. Values are based on [12] – Table 3 and [13] – Table C.5.

Table 5. Fuel emission factors

/	HFO	MDO	LNG
E _{F(CO₂)}	3170	3170	2688
E _{F(SO_x)}	20 x S%	20 x S%	0.027
E _{F(NO_x), Slow Speed}	87	87	8.16
E _{F(NO_x), Medium Speed}	57	57	5.35
E _{F(PM)}	7.6	7.6	0.21

4 Study results

In Table 6 are shown the results attained by equations (1), (2) and (3) regarding the fuel used for the parameters set in Chapter 3.

Table 6 Fuel consumption for operation the vessels for period of 1 year

MSC AMY		
	ME FC [tonnes]	AE FC [tonnes]
Initial	15217 HFO	1445 MDO
Alternative	11441 LNG + 298 MDO	3033 LNG + 53 MDO
MSC ATHENS		
	ME FC [tonnes]	AE FC [tonnes]

Initial	39762 HFO	11735 MDO
Alternative	31635 LNG + 838 MDO	11526 LNG + 226 MDO
MSC HAMBURG		
	ME FC [tonnes]	AE FC [tonnes]
Initial	49990 HFO	12425 MDO
Alternative	38176 LNG + 1163 MDO	12204 LNG + 240 MDO

In Table 7 are shown the energy costs regarding the fuel used for operation the ships in a period of 1 year. The results are derived by equation (4)

Table 7. Energy costs for operating the ships in a period of 1 year with both propulsion options

MSC AMY			
Initial	HFO Costs [\$]	MDO Costs [\$]	Total Costs [\$]
	6 124 681	1 612 212	7 736 893
Alternative	LNG Costs [\$]	MDO Costs [\$]	Total Costs [\$]
	2 436 797	195 716	2 632 513
MSC ATHENS			
Initial	HFO Costs [\$]	MDO Costs [\$]	Total Costs [\$]
	16 004 241	6 542 207	22 456 448
Alternative	LNG Costs [\$]	MDO Costs [\$]	Total Costs [\$]
	7 266 249	593 169	7 859 410
MSC HAMBURG			
Initial	HFO Costs [\$]	MDO Costs [\$]	Total Costs [\$]
	20 120 899	6 927 038	27 047 937
Alternative	LNG Costs [\$]	MDO Costs [\$]	Total Costs [\$]
	8 481 505	781 743	9 263 248

Note: The fuel costs may vary depending on the sailing region of the ships, therefore the energy costs savings could be quite different.

In Figure 3 is depicted the percentage reduction of the energy costs achieved due to the fuel type selection for the ship's propulsion system for period of 1 year.

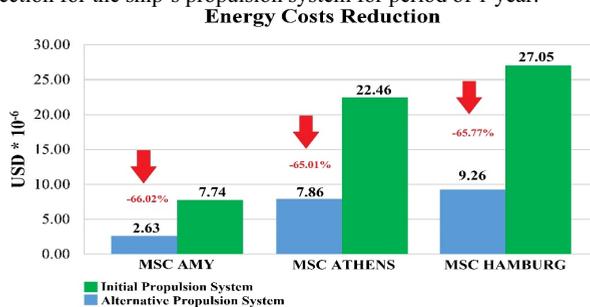


Fig. 3. Energy costs reduction level in percentages

In Table 8 are given the quantified values for harmful gases and substances emitted into the atmosphere due to the fuel burning. The calculations are performed by equations (5), (6), (7) and (8).

Table 8. GHG Emissions separated due to the operation of the ships for period of 1 year

Observed object	CO ₂	SO _x	NO _x	PM
MSC AMY Initial	57403.8	1082.5	1488.7	137.6
MSC AMY Alternative	40020.6	3.7	129.6	5.7
MSC ATHENS Initial	163245.5	2853.8	4128.2	391.4
MSC ATHENS Alternative	119391.1	10.9	380.5	17.2
MSC HAMBURG Initial	197855.5	3573.8	5057.4	474.4
MSC HAMBURG Alternative	139867.0	14.4	402.1	21.2

Note: All units are in metric tonnes.

In Figures 4, 5, 6 and 7 is depicted the percentage reduction of the GHG emissions achieved due to the fuel type selection for the ship's propulsion system for period of 1 year.

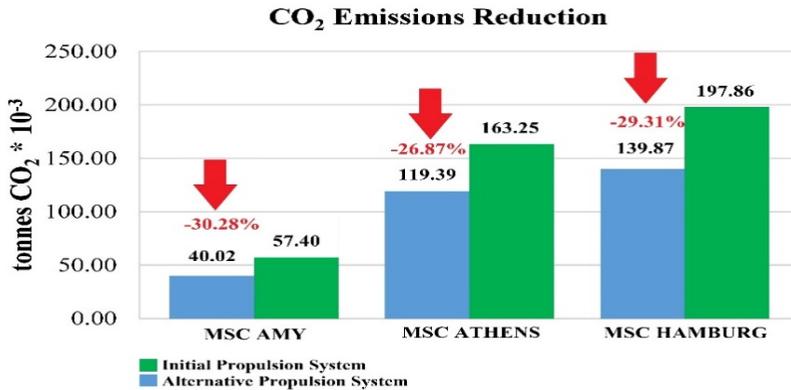


Fig. 4. CO₂ Emissions reduction level in percentages

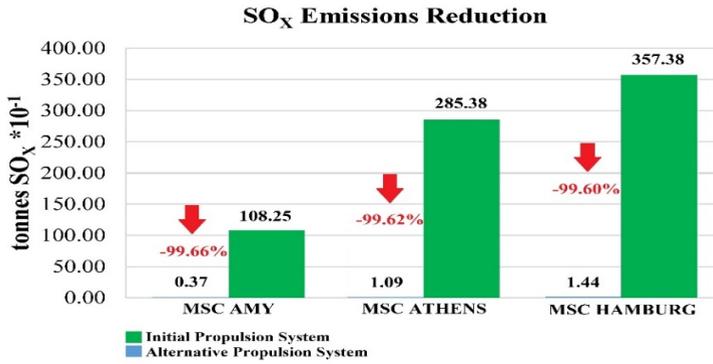


Fig. 5. SO_x Emissions reduction level in percentages

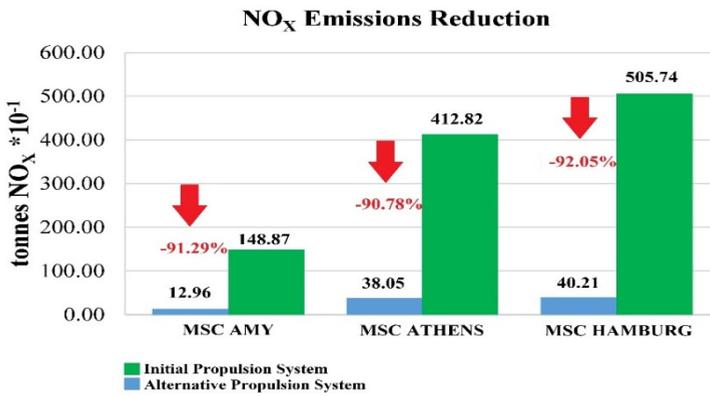


Figure 6. NO_x Emissions reduction level in percentages

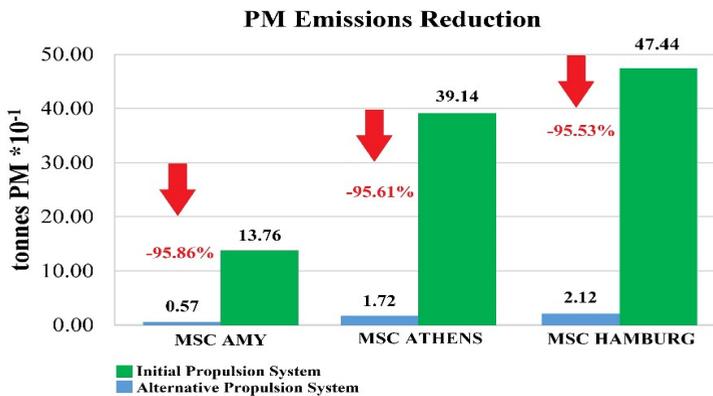


Fig. 7. PM Emissions reduction level in percentages

5 Conclusions

In the current study three types of container vessels has been observed. For each ship the initial equipped and alternative modern propulsion systems has been studied. Calculations regarding the energy costs and GHG emitting has been performed with purpose to make an assesment of the ecology performance of each ship.

Based on the calculation methodology set out in Chapter 3 a significant advantages of the modern dual-fuel engines over the conventional diesel engines widely used in the shipping has been found.

The fuel consumption forming a major part of the energy costs of each ship is significant reduced due to using a dual-fuel technology. An average reducing of the energy costs with 65.6% is observed based on the results published in Chapter 4.

Along with the notable annual fuel consumption and energy costs reduction, the less environment pollution rendered due to use of less polluting fuels should not be neglected.

Due to the methodology set out in Chapter III also and remarkable GHG reduction has been accounted. An average reduction of main GHG gases like CO₂, SO_x, NO_x and PM respectively with 28.82%, 99.63%, 91.37% and 95.67% is observed. The results from the conducted study displaying a significant reducing of the CO₂ and NO_x, and also almost full elimination of the SO_x and PM when using dual-fuel engines.

Owing to the switching to modern propulsion systems working on Dual-Fuel an option is given to the shipowners to significantly reduce their fuel expenditures as along with that to help for state of the environment improvement. Dual-Fuel technology likewise contributes to fulfil the stricter energy efficiency requirements introduced by IMO.

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