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Influence evaluation of the ship propulsion system on the energy efficiency for small, medium and large container vessels

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Abstract. The transportation of goods worldwide has a vital meaning for the entire of humanity. The seaborne transport is considered to be the most efficient – economically and environmentally friendly way to convey large amount of goods when compared to the other transport options available. Marine vessels contribute for the carriage of about 90 percent of the worldwide trade and a significant part of the goods delivered by sea are performed by container vessels. Even considered as the most efficient way of transportation the negative aspects of the shipping should not be neglected. The fuels intended for the ship propulsion generating enormous amounts of Greenhouse gases (GHG) and harmful emissions which are directly released into the atmosphere. When it comes to Energy Efficiency of the ships, the proper selection of the propulsion system and the fuel type used are essential with regard to achieve the best values. In the current paper a diverse alternative propulsion system options in order to achieve maximum Energy Efficiency on various sizes of container vessels will be analyzed.

1 Introduction

The basic goal set in front of the today's worldwide shipping is to reduce the negative effect caused by the generation of the GHG and harmful gases produced when ship's operation. The goods transportation via ships is considered for about 90 percent of the global trade and the main ships type involved in it is the container class.

In terms of value, global seaborne container trade is believed to account for approximately 60 percent of all world seaborne trade, which was valued at around 12 trillion U.S. dollars in 2017 [1].

The GHG emissions — including carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O), expressed in CO_2e — 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 CO_2 emissions, while in 2018 this amount grew 9.3% to 1,056 million tonnes of CO_2 emissions. The share of shipping emissions in global anthropogenic emissions has increased from 2.76% in 2012 to 2.89% in 2018 [2].

The values for global CO_2 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 CO_2 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

Despite the shipping industry could be classified as the most environmentally friendly and economically profitable way to transport a large amount of goods the negative effect of the industry should also be considered. Annually the worldwide shipping uses a large amount of fossil fuels to operate the available fleet.

Even with the newly adopted requirements known as IMO 2020 which limits the sulphur content in the fuels used onboard of the ships to 0.50 % outside Emission Control Areas (ECAs) and 0.10 % inside ECAs, the ships equipped with devices for exhaust gas treatment are still able to use heavy fuel oils (HFO) with high sulfur content whose burning in the main engines lead to serious environmental pollution.

Of the around 56,000 merchant ships trading internationally, some 5400 are container ships, thus means that the container class accounts for about 10% of the global merchant fleet.

In Figure 1 is shown the number of the ships included in the global merchant fleet and the shares respectively for each ship's class engaged in the worldwide trading until 1st January 2020.

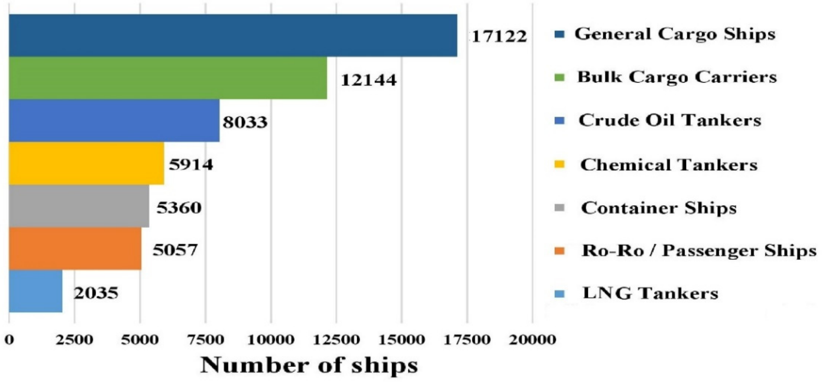

Fig. 1. Shares by ship's class involved in the global merchant fleet (*Source* - www.statista.com)

Three ship classes accounted for 55% of the total shipping CO_2 emissions: container ships (23%), bulk carriers (19%), and oil tankers (13%), also these three ship classes accounted for 84% of total shipping transport supply (deadweight tonne nautical miles, or dwt-nm) [3].
In Figure 2 are depicted the CO_2 emissions generation depending on the ship's class (Source – [3]).

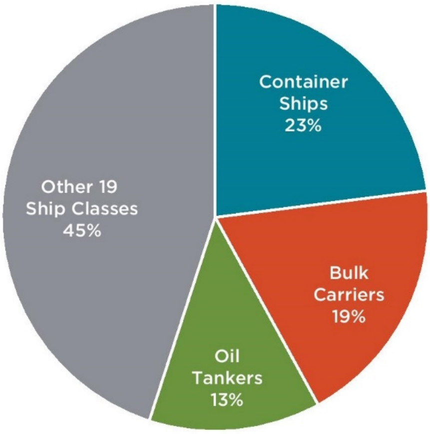

Fig. 2. Shares of CO_2 emissions by ship's class

With purpose to achieve better Energy Efficiency and state of the environment improvement, the International Maritime Organization (IMO) and Marine Environment Protection Committee (MEPC) established some requirements in connection with reducing the GHG generated by the 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, paving the way for the regulations on EEDI and SEEMP to be smoothly implemented by Administrations and industry [4].

The EEDI represents a non-prescriptive, performance- based mechanism that leaves the choice of technologies to use in a specific ship design to the industry. As long as the required energy efficiency level is attained, ship designers and builders would be free to use the most cost-efficient solutions for the ship to comply with the regulations. EEDI is requiring a minimum energy efficiency level for new ships by stimulating continued technical development of all the components influencing the fuel efficiency of a ship and by separating the technical and design-based measures from the operational and commercial ones [5].

The ship's energy efficiency could be represented as a function of its main and auxiliary engines power and the work fulfilled (cargo transported for certain time). The required speed of the ship and the engines power can be reached by various types of propulsion systems.

In order to comply with the IMO requirements regarding the GHG generation, the ship engine manufacturers developed much more efficient engine types which are able to work either with gaseous or with conventional fuels. Increasingly wider applications are finding the so-called Dual-Fuel Engines, which are able to operate with gaseous fuels and a small portion of diesel as a pilot fuel.

The energy efficiency of the ship could be improved and therefore the GHG emitting reduced by applying some of the various ways listed below:

- ***Pay more attention on the proper engine selection;***
- ***Using fuels with lower carbon content;***
- ***Speed reduction with purpose to decrease the Specific Fuel Oil Consumption (SFOC);***
- ***Implementation of innovative and renewable technologies reducing the CO_2 emissions.***

If we consider the service speed of the ship and its deadweight as a constant value, we have to pay much more attention when choosing the propulsion system with purpose to select the proper one which leads to EEDI improvement and GHG reduction.

The aims set in the current paper is to describe a methodology for selecting the proper propulsion system type for small, medium and large container vessels based on calculations of various systems, comparing the energy efficiency achieved with each and choosing the most efficient one with regard to fulfill the IMO requirements intended to GHG Emissions.

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 distribution of the observed ships is approximately 55.2% of the total container ships by 2019.

In Figure 3 is shown the distribution of the container vessels by their size (Source – [6]).

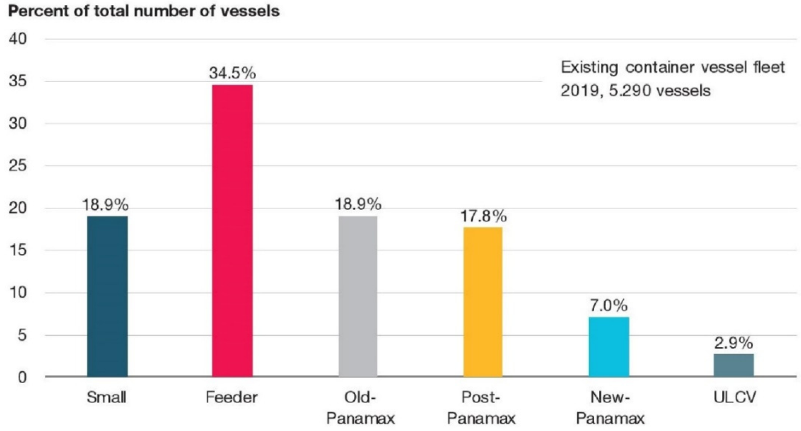

Fig. 3. Container vessels distribution by 2019

2 Marine propulsion system types

Nowadays there are a various options to configure a ship’s propulsion system. The fuel oil consumption of the propulsion system mainly describing its cost efficiency is only the one side of the coin, but the other one is the ecology and the energy efficiency offering the use of each system type.

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 [7].

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

With the constantly tightening requirements regarding the ecology the ships have to comply with, the shipping industry have to adapt and implement new technologies.

One of the methods to comply with the requirements is to run the fleet with engines using fuels with lower or none carbon content in comparison with the widely used conventional fuels like HFO and MDO.

The engines used in the ship's propulsion arrangement could be classified by various features, some of them listed below:

- ***By working cycle accomplishment – 2-stroke and 4-stroke engines;***
- ***By their speed – Low-speed, Medium-speed and High-speed engines;***
- ***By the fuel type used – Diesel or Dual-Fuel engines.***

In the past decade, dual-fuel marine diesel engines using LNG as a secondary fuel, from either an LNG fuel tank or boil-off-gas, were developed and applied on board merchant vessels as an option to fulfil the IMO NOx Tier III regulations [8].

On Figure 4 is shown the typical arrangement commonly used in the container ship propulsion systems.

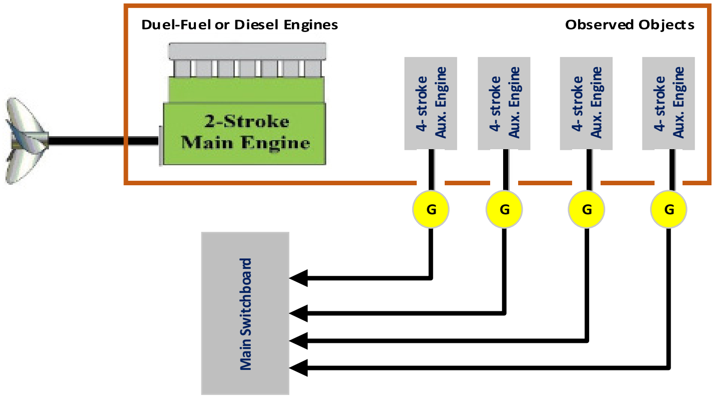

Fig. 4. Typical container ship propulsion system arrangement

In the current article will be considered various options for propulsion system arrangements for small, medium and large container vessels. This will be achieved by comparison of diverse propulsion systems using diesel or dual-fuel engines working on 2 or 4-stroke cycle. The comparison of the propulsion systems will be performed based on the achieved EEDI values depending on the fuel type used.

3 Attained and Required EEDI calculation methodology

The seaborne transport represents the most effective way of transport used nowadays, but the GHG and harmful emissions produced by the fossil fuels used in the internal combustion engines is a quite serious issue. Basically, the ship's energy efficiency is measured by the amounts of emissions radiated in the atmosphere and this effect could be accounted by calculating the ship's Attained EEDI and after that comparing it to the Required EEDI strictly depending on the ship's specific type and its capacity.

Attained EEDI

EEDI is mandatory for each new-built ship with gross tonnage equal to or above 400 GT and could be considered as the most valuable indicator for her energy efficiency GHG emission level. EEDI is expressed in grams CO_2 per tonne mile.

The methodology and requirements for Attained EEDI calculation for new ships are published by MEPC in [9].

The formula intended for Attained EEDI calculation of the ship includes CO2 emissions generated by the work done by the main and auxiliary engines, shaft motor and shaft generators and the reduction derived by the implementation of innovative energy efficient technologies. Thus, all is divided by the transport work done which could be represented as the multiplication of the ship's deadweight and her service speed.

The simplified formula for Attained EEDI calculation is listed below:

$$Attained\ EEDI = \frac{(P_{ME(i)} \times C_{FME(i)} \times SFC_{ME(i)}) + (P_{AE} \times C_{FAE} \times SFC_{AE})}{f_i \times f_c \times f_l \times Capacity \times f_w \times V_{ref}} \tag{1}$$

Where:
$P_{ME(i)}$ – 75% of the rated installed power for each main engine (i);
P_{AE} – is the required auxiliary engine power to supply normal maximum sea load including necessary power for propulsion machinery/systems and accommodation;
$C_{FME(i)}$ – conversion factor between fuel consumption and CO_2 emissions for main engine(s);
$C_{FAE(i)}$ – conversion factor between fuel consumption and CO_2 emissions for auxiliary engine(s);
$SFC_{ME(i)}$ – specific fuel consumption of main engine at 75% of the rated power of the engine;
SFC_{AE} – specific fuel consumption of auxiliary engine at 50% of the rated power of the engine;
Capacity – for container vessels 70% of deadweight should be used as capacity;
V_{ref} – ship's speed at 75% power of the main engine;
f_i – capacity factor;
f_c – cubic capacity conversion factor;
f_l – factor for general cargo ships equipped with cranes and other cargo related gear;
f_w – weather factor.

If Power Take In / Power Take Off devices (PTI/PTO) and/or renewable energy efficiency technologies are used in composition of the ship propulsion system, their effect should also be accounted. This is achieved by supplementing the numerator of equation (1) with equation (2):

$$\left(\left(f_j \times P_{PTI(i)} - f_{eff(i)} \times P_{AEeff(i)}\right) C_{FAE} \times SFC_{AE}\right) - \left(f_{eff(i)} \times P_{eff(i)} \times C_{FME} \times SFC_{ME}\right) \tag{2}$$

Where:
f_j – correction factor for specific ship specific design elements;
$P_{PTI(i)}$ - 75% of the rated power consumption of each shaft motor divided by the weighted average efficiency of the generator(s);
$f_{eff(i)}$ - the availability factor of each innovative energy efficiency technology;
$P_{AEeff(i)}$ – is the auxiliary power reduction due to innovative electrical energy efficient technology;
$P_{eff(i)}$ - the output of the innovative mechanical energy efficient technology for propulsion at 75% main engine power;

The required auxiliary engine power to supply normal maximum sea load including necessary power for propulsion machinery/systems and accommodations could be found by the following two principles:

For ships with a total propulsion power of 10000 kW or above, PAE have to be defined as follows:

$$P_{AE} = \left(0.025 \times \left(MCR_{ME(i)} + \frac{P_{PTI(i)}}{0.75}\right)\right) + 250 \tag{3}$$

For ships with a total propulsion power below 10000 kW, P_{AE} have to be defined as follows:

Where:

$MCR_{ME(i)}$ – maximum continuous rating of the main engine;

$$P_{AE} = \left(0.05 \times \left(MCR_{(i)} + \frac{P_{PTI(i)}}{0.75}\right)\right) \tag{4}$$

Generally, the full formula consisting of equations (1) and (2) could be simplified to much easier for understanding equation (5) as follows:

$$EEDI = \frac{CO_2\ Emissions\ Generated}{Transport\ work} \tag{5}$$

More specific information regarding the calculation methodology, parameters and coefficients used for calculation of the EEDI for each ship could be found in [7].

Required EEDI

According to the requirements adopted by IMO and MEPC, each new-built ship EEDI value have to be in compliance with the reference value calculated for the corresponding ship type.

The REEDI is going to be decreased gradually and this is planned to be achieved in three phases as the last one has to be introduced in force from 1st January 2025 and aims for a reduction of REEDI by 30%.

On Figure 5 are shown the reduction phases of REEDI thru the years [Source – [10])

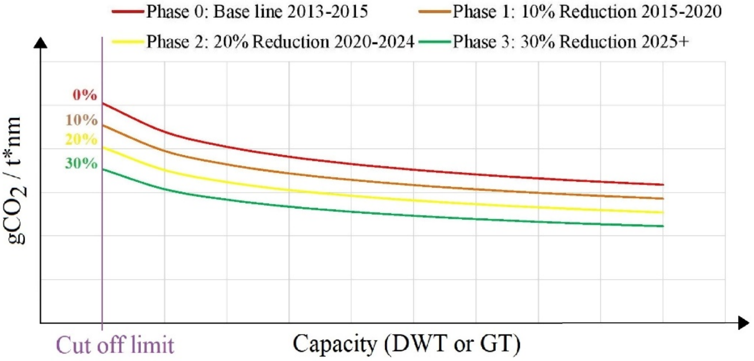

Fig. 5. REEDI reduction phases

The formula for calculating the REEDI is listed below:

$$REEDI = a \times b^{-c} \tag{6}$$

In equation (6) the parameters “a” and “c” are determined from the regression curve fit and they are specified in [9] and [10], the parameter “b” expresses the deadweight of the ship.

4 Calculations and study results

With regard to fulfil the goals set in this paper and to perform the necessary calculations for the propulsion systems which we intend to observe, first we have to choose some real ships or projects. For the purpose of this paper, we have chosen real container vessels of MSC company, which is one of the biggest companies in this field. 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 [14].

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

For the purpose of this paper, 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

For both – initial and alternative propulsion systems identical calculations for determination of the Attained EEDI have been conducted.

The calculations are performed according to the requirements exposed in Section 2 of the current article. 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.

The reference speed of the observed ships at the relevant engine load necessary for EEDI calculations is estimated based on the equation (8) listed below:

$$P_B = c \times V^i \tag{8}$$

Where:
P_B – ME Power, [kW];
c – constant;
V – Ship's speed, [knots];
i – exponent, depending on the ship's size. For first estimations widely used in the practice is the adoption of i=3.

In Table 4 are given the full input data necessary for the calculations performed in the current article for Attained and Required EEDI.

Table 4. Input data necessary for the calculations of EEDI and REEDI for the observed ships

Ship	**MSC AMY**	**MSC ATHENS**	**MSC HAMBURG**
ME Power at 75% load, [kW]	12735	35572.5	44835
ME SFOC at 75% (initial), [g/kWh]	170.5 (HFO)	159.5 (HFO)	159.1 (HFO)
ME SFOC at 75% (alt.), [g/kWh]	128.2 (LNG) 3.34 (MDO)	126.9 (LNG) 3.36 (MDO)	121.5 (LNG) 3.70 (MDO)
DG Power (Equation 3), [kW]	568.38	1435.75	1744.5
DG SFOC at 50% (initial), [g/kWh]	196.5 (MDO)	197.0 (MDO)	197.0 (MDO)
DG SFOC at 50% (alt.), [g/kWh]	206.1(LNG) 3.60 (MDO)	193.5(LNG) 3.80 (MDO)	193.5(LNG) 3.80(MDO)
C_F (HFO)	3.114		
C_F (MDO)	3.206		
C_F (LNG)	2.750		
Deadweight, [tonnes]	22308	95380	184100
Ref. Speed, [knots]	18.63	19.99	20.9
Coeff. „a“	174.22		
Coeff. „-c“	0.201		

In Tables 5 and 6 are shown the calculated data regarding the Required and Attained EEDI for each ship using respectively the initial and the alternative proposed propulsion options.

Table 5. REEDI and AEEDI for the observed ships equipped with the initial propulsion systems

Ship	**MSC AMY**	**MSC ATHENS**	**MSC HAMBURG**
Base REEDI (2013÷2015)	23.28	17.39	15.23
Phase 1 (2015÷2020)	20.96	15.65	13.71

Phase 2 (2020÷2024)	18.63	13.91	12.19
Phase 3 (2025+)	16.30	12.17	10.66
Attained EEDI	24.7	13.94	8.65

Table 6. REEDI and AEEDI for the observed ships equipped with the alternative propulsion systems

Ship	**MSC AMY**	**MSC ATHENS**	**MSC HAMBURG**
Base REEDI (2013÷2015)	23.28	17.39	15.23
Phase 1 (2015÷2020)	20.96	15.65	13.71
Phase 2 (2020÷2024)	18.63	13.91	12.19
Phase 3 (2025+)	16.30	12.17	10.66
Attained EEDI	17.24	10.18	6.11

Note:

- Green color - In compliance;
- Red color – Non-compliance.

In Figure 6 is shown the reduction in percentages between the Attained EEDI for initial and alternative propulsion systems.

Depending on the reduction percentages could be done a basic estimation of the positive effect rendered only by the propulsion system type.

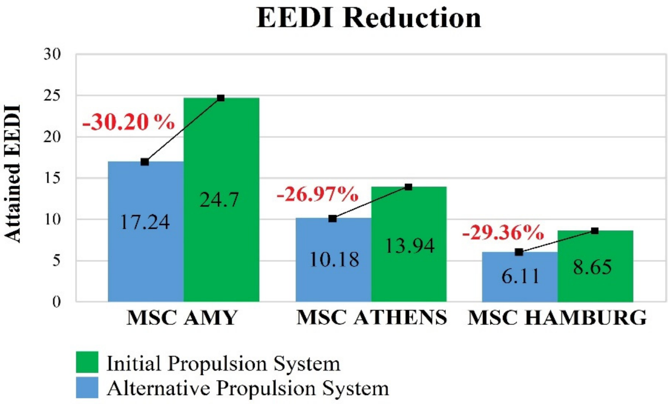

Fig. 6. EEDI reduction in percentages due to alternative propulsion system use

On Figures 7, 8 and 9 are graphically illustrated the calculated values for Attained EEDI regarding the observed in the current article ships respectively for the initial equipped and alternative propulsion systems proposed.

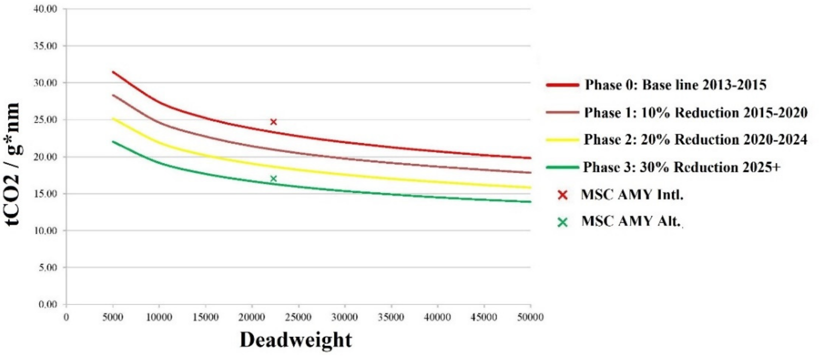

Fig. 7. Attained EEDI for small container vessel

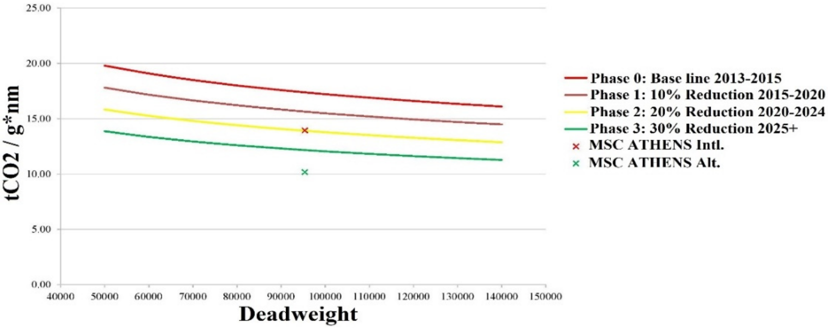

Fig. 8. Attained EEDI for medium container vessel

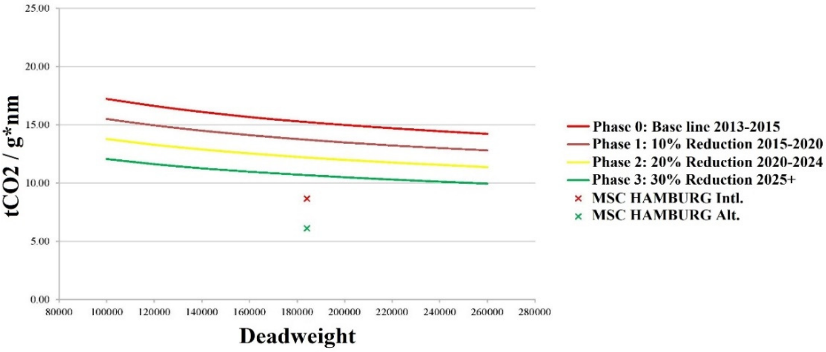

Fig. 9. Attained EEDI for large container vessel

5 Conclusions

In the current paper had been observed three types of container vessels depending on their size – small, medium and large respectively. For the analyzed ships have been considered their initial equipped propulsion systems and then alternative modern options for the propulsion working on the Dual-Fuel principle have been proposed.

Based on the calculations performed in Section 3 of the present paper, first for the initial propulsion systems and then for the alternative options a significant improvement of the Attained EEDI has been found for each ship.

The improvement of the EEDI amounts to 30.20% for small, 26.97% for medium and 29.36% for large container vessels respectively. Average EEDI enhancement of 28.84% has been accounted for the three types of vessels observed.

Thanks to the switching to modern propulsion systems working on Dual-Fuel principle the observed ships are able to fulfil the stricter energy efficiency requirements introduced by IMO.

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