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Original scientific paper

Assessment of Energy Efficiency for the Existing Cargo Ships*

Milan Kalajdžić, Matija Vasilev, Nikola Momčilović

Abstract: In order to address the decarbonization policy, International Maritime Organization (IMO) has been dealing with energy efficiency of ships for more than a decade. Firstly, procedures for energy efficiency assessment are introduced through the regulative, but only for new ships. Consequently, IMO also introduced energy efficiency criterion for already built ships that is set to be applicable starting from 2023. Regulative is already having an impact on ship design. While the new ships can be adapted in design phase, built ones will not have so many options. So far, almost all the solutions include reduction of the speed, i.e., slow steaming. Nevertheless, there are numerous technical and operational measures. The paper presents the calculation of energy efficiency performed for the fleet of existing 11 cargo ships categorized into four different ship classes. Calculation is based on the current IMO regulations covering the evaluation of energy efficiency of existing ships index (*EEXI*). Input parameters for analysis are obtained using two approaches: technical files (design parameters of the ship) & sea-trial reports and statistical method (when technical files & sea-trail reports are not available). Authors examined if the difference in two input approaches and potential class notation change could lead to different energy efficiency evaluation results. Moreover, the main goal of the research was to investigate on how the present conventionally designed cargo ships compare to the novel regulations.

Keywords: EEXI, EEDI, Energy efficiency, Energy efficiency existing ships.

1. Introduction

Following the emerging decarbonization policies in various industries, the Marine Environment Protection Committee (MEPC), working under the framework of the International Maritime Organization (IMO), introduced a procedure for the evaluation of energy efficiency of new ships. The regulations started to apply in 2013 while its requirements have been strengthened over every five years, starting from 2015. Procedure asked for the calculation of attained (*attained EEDI*) and required energy efficiency designed

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index (*required EEDI*), as shown in [1]. In order to satisfy the criterion, ship's *attained EEDI* had to be lower than its *required EEDI*. If not, ship has to make design changes in order to meet the regulative. To large extent, this pushed the investigations towards the energy saving devices. However, the major and most obvious change over the years appears to be the speed and power reduction.

Already built ships have not been neglected since the corresponding regulative is introduced in IMO's strategy for the short- and long-term decarbonization of shipping [2, 3, 4]. Thus, Intersessional Working Group (ISWG) of the IMO delivered a procedure for the evaluation of energy efficiency of existing ships, see [5]. The procedure includes methods for the calculation of attained (*attained EEXI*) and required energy efficiency existing ship index (*required EEXI*). *EEXI* is largely based on *EEDI* concept. Therefore, a*ttained EEXI* should be lower than *required EEXI* for the ship to comply with the regulative. *EEXI* requirements are set to start applying from 2023 and are obligatory for ships having GT above 400 and while satisfying MARPOL Annex VI.

Authors of this paper have been studying the influence of novel environmental policies on existing ships. This was the case, particularly, for multipurpose fleet of sea-going ships [6] and furthermore, for similar ships in size but different regarding their class [7]. Hence, this paper is an extension of the paper presented in [7]. Here, energy efficiency evaluation is performed on 11 cargo ships that falls into four classes whereas in [7] only four ships are included. In the following sections, the various built ships are presented along with their particulars. Besides, authors presented the procedure and results for the calculation of *EEXI* for each of the ship, followed by the sensitivity assessment for various input variations. Finally, authors discussed potential solutions for energy efficiency improvement. More on energy efficiency considerations for cargo ships one can find in literature, see [8] and [9].

2. Database of ships

Energy efficiency existing ship index (*EEXI*) is calculated for the 11 cargo ships for which authors have obtained reliable data from design documentation and sea-trial reports. All ships are falling into four different classes, namely: two general cargo ships, three bulk carriers, three tankers and three containerships. The main particulars are presented graphically, see Figs. 1 and 2. Each is represented by 11 columns that denote to 11 ships. Going from left to the right of each column respective ships with their classes (and years of built) are illustrated in the following order: 1 – general cargo (2001), 2 – general cargo (2007), 3 – bulk carrier (2010), 4 - bulk carrier (2017), 5 - bulk carrier (2011), 6 – tanker (2010), 7 - tanker (2007), 8 - tanker (2007), 9 –

container ship (2006), 10 - container ship (2008), 11 - container ship (2017). This notation is used as an agenda in diagrams. For some of particulars there are no full list of data for each ship. For instance, first two ships (1 and 2) have no data on design *DWT*, so the corresponding column values starts from ship no. 3, see Fig. 2.

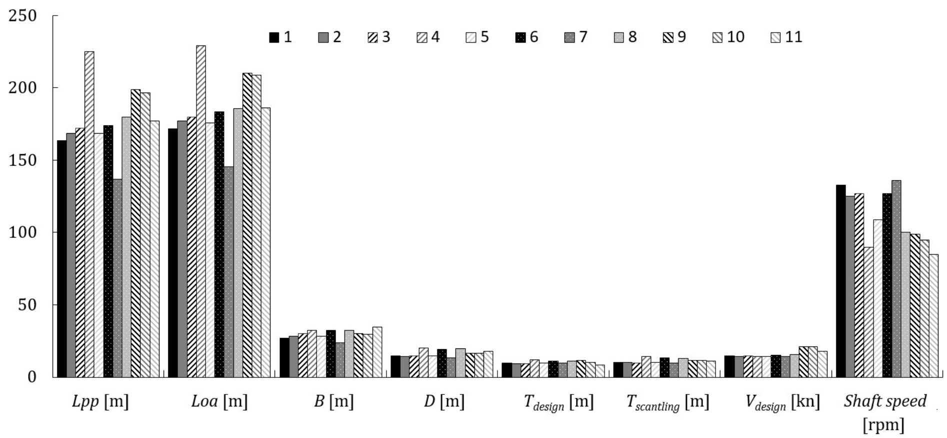

Fig. 1 – *Ship particulars.*

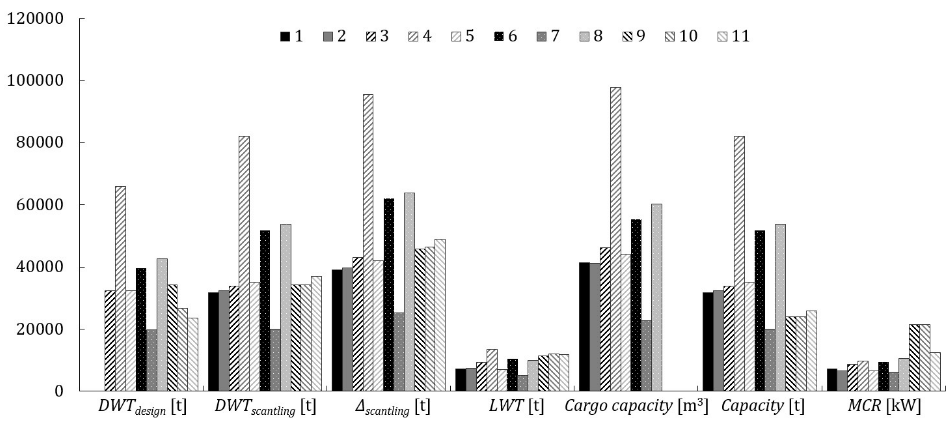

Fig. 2 – *Ship particulars.*

3. *Required EEXI* calculation

Required EEXI is a criterion for energy efficiency evaluation. Therefore, *attained EEXI* must be lower that *required EEXI* so that ship can be regarded as energy efficient according to IMO. ISWG [10] provided the *required EEXI* calculation procedure for built ships as the same as in case of *required EEDI* for new ships, see eq. (1). *Y* is a reduction factor and is chosen based on ships class and *DWT*. *Y* and other coefficients used are given in Table 1. Consequently, a diagram of *required EEXI* depending on *DWT* is plotted in Fig. 3.

$$Required\ EEXI = \left(1 - \frac{Y}{100}\right) \cdot Reference\ line\ value \qquad (1)$$
$$Reference\ line\ value = a \cdot b^{-c}$$

Table 1 – *Coefficients for the calculation of required EEXI.*

	Ship No.	*Y*	*a*	*b=DWT*	*c*	*Req. EEXI*
General cargo ships	1	30	107.48	31659	0.216	8.023
	2			32286		7.989
Bulk carriers	3	20	961.79	33762	0.477	5.322
	4			82049		3.485
	5			35009		5.231
Tankers	6	20	1218.8	51672	0.488	4.886
	7			19996		7.765
	8			53815		4.790
Container ships	9	20	174.22	34254	0.201	17.089
	10			34331		17.081
	11			36946		16.831

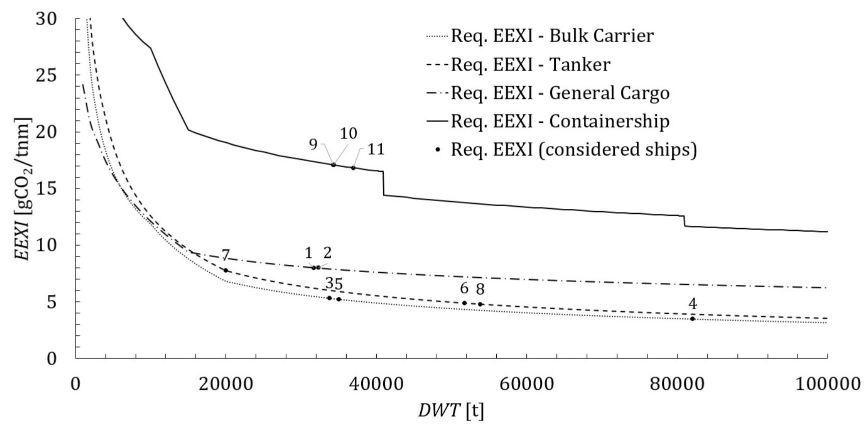

Fig. 3 – *Required EEXI.*

4. *Attained EEXI* calculation

Attained EEXI calculation procedure for built ships corresponds to the *EEDI* for new ships. Hence, according to IMO regulative, ships that were newly built at the time when only *EEDI* regulative for new ships were available can use their already calculated *attained EEDI* instead of calculating *attained EEXI*. Nevertheless, *attained EEXI* is calculated according to [5], as in eq. (2). Label "*" in eq. (2) means that if part of the normal maximum sea load is provided by shaft generators, SFC_{ME} and C_{FME} may, for that part of the power, be used instead of SFC_{AE} and C_{FAE}. Moreover, label "**" states that, in case of $P_{PTI(i)} > 0$, the average weighted value of ($SFC_{ME} \cdot C_{FME}$) and ($SFC_{AE} \cdot C_{FAE}$) is to be used for calculation of P_{eff}.

$$
\begin{gathered}
[\left(\prod_{j=1}^{n} f_j\right)\left(\sum_{i=1}^{nME} P_{ME(i)} \cdot C_{FME(i)} \cdot SFC_{ME(i)}\right) + (P_{AE} \cdot C_{FAE} \cdot SFC_{AE} *) \\
+ \\
+\left(\left(\prod_{j=1}^{n} f_j \cdot \sum_{i=1}^{nPTI} P_{PTI(i)} - \sum_{i=1}^{neff} f_{eff(i)} \cdot P_{AEeff(i)}\right) C_{FAE} \cdot SFC_{AE}\right) \\
- \\
-\left(\sum_{i=1}^{neff} f_{eff(i)} \cdot P_{eff(i)} \cdot C_{FME} \cdot SFC_{ME} **\right) \cdot \\
\cdot \frac{1}{f_i \cdot f_c \cdot f_l \cdot Capacity \cdot f_w \cdot V_{ref} \cdot f_m}
\end{gathered} \tag{2}
$$

Note that in this paper the following assumptions are made: shaft motors are not installed (P_{PTI}=0) on these ships, nor innovative mechanical energy efficient technologies on main or auxiliary engine ($P_{eff} = 0$, $P_{AEeff} = 0$). Furthermore, two approaches are performed for inputs. In the first one (case 1), statistically obtained data are used as an input. In the second one (case 2), semi-statistical data are applied, which were based on available documentation and sea-trail report for the particular ship. Nonetheless, no ship from the database has engine power limiter installed so the eq. (2) can be simplified to the level of eq. (3).

$$
Attained\ EEXI = \frac{P_{ME} \cdot C_{FME} \cdot SFC_{ME} + P_{AE} \cdot C_{FAE} \cdot SFC_{AE}}{f_i \cdot f_c \cdot f_l \cdot Capacity \cdot f_w \cdot V_{ref} \cdot f_m} \tag{3}
$$

All parameters used in eq. (3) are determined using guidelines from [4] and presented in Tables 2-4. Still, some of them need clarification. Power of main engine (P_{ME}) corresponds to the 75% of the installed power (MCR). P_{AE} is auxiliary engine power required to supply normal maximum sea load also taking into account power for propulsion of machinery/systems and accommodation. C_F is a conversion factor between fuel consumption and CO_2 emissions. Subscript "*ME*"refers to the main and subscript "*AE*" to the auxiliary engine.

Table 2 – *Input parameters.*

	Ship no.	P_{ME} [kW]	P_{AE} [kW]	Fuel type ME	Fuel type AE	C_{FME} [tCO2/tFuel]	C_{FAE} [tCO2/tFuel]	SFC_{ME} [g/kWh]	SFC_{AE} [g/kWh]
General cargo ships	1	5369	358.0	Diesel	Diesel	3.206	3.206	167.9	204.7
	2	4965	331.0	Diesel	HFO	3.206	3.114	168.1	215.0
Bulk carriers	3	6435	429.0	Diesel	Diesel	3.206	3.206	171.5	218.3
	4	7350	490.0	Diesel	Diesel	3.206	3.206	163.1	235.3
	5	4992	332.8	Diesel	HFO	3.206	3.114	183.8	215.0
Tankers	6	7110	474.0	Diesel	HFO	3.206	3.114	175.4	215.0
	7	4613	307.5	Diesel	Diesel	3.206	3.206	180.7	208.2
	8	7965	515.5	Diesel	HFO	3.206	3.114	171.0	215.0
Cont. ships	9	16170	789.0	Diesel	Diesel	3.206	3.206	174.9	208.6
	10	16118	787.3	Diesel	HFO	3.206	3.114	169.8	215.0
	11	9375	562.5	Diesel	Diesel	3.206	3.206	165.6	209.2

Table 3 – *f factors.*

	Ship no.	f_c [-]	f_l [-]	f_m [-]	f_w [-]	f_i [-]
General cargo ships	1	1.000	1.009	1.000	1.000	1.000
	2	1.000	1.009	1.000	1.000	1.000
Bulk carriers	3	1.000	1.000	1.000	1.000	1.022
	4	1.000	1.000	1.000	1.000	1.013
	5	1.000	1.000	1.000	1.000	1.000
Tankers	6	1.035	1.000	1.000	1.000	1.000
	7	1.077	1.000	1.000	1.000	1.000
	8	1.000	1.000	1.000	1.000	1.000
Container ships	9	1.000	1.000	1.000	1.000	1.000
	10	1.000	1.000	1.000	1.000	1.000
	11	1.000	1.000	1.000	1.000	1.000

Table 4 – *Reference speeds and power.*

	Ship no.	$V_{ref,avg}$ [kn]	$V_{ref,app}$ [kn]	V_{ref} [kn]	MCR_{avg} [kW]	MCR [kW]
General cargo ships	1	17.27	13.72	14.14	12246	7159
	2	17.34	13.34	13.74	12468	6620
Bulk carriers	3	14.13	14.59	12.88	6683	8580
	4	14.48	13.31	13.51	10803	9800
	5	14.15	13.33	13.62	6815	6656
Tankers	6	14.59	13.72	13.62	9771	9480
	7	13.87	13.47	14.63	5751	6150
	8	14.62	14.18	15.70	9995	10620
Container ships	9	21.88	20.22	20.84	23738	21560
	10	21.89	20.19	19.92	23793	21490
	11	22.19	16.67	15.95	25662	12500

4.1. *Attained EEXI* – Case 1

Case 1 here represents the approach in which the inputs for the *EEXI* evaluation are determined according to statistics of similar ships taken from in IMO guidelines. This approach can be used when no speed-power curve nor sea-trail report are available. Therefore, according to [5] ship speed is determined by eq. (4) using mean distribution of ship speed and engine power for the corresponding *DWT* and ship type. Moreover, considering [5], specific fuel consumptions are assumed as: $SFC_{ME,app}$ = 190 g/kWh and $SFC_{AE,app}$ = 215 g/kWh.

$$V_{ref,app} = \left(V_{ref,avg} - m_v\right) \cdot \left[\frac{P_{ME}}{0.75 \cdot MCR_{avg}}\right]^{\frac{1}{3}} \tag{4}$$

4.2. *Attained EEXI* – Case 2

When speed-power curve is available from sea-trail report and the actual specific fuel consumption data are available, then a semi-statistical approach can be used to obtain input data. Considering [5], reference speed is calculated for general cargo ships, see eq. (5) and for container ships, bulk carriers and tankers, see eq. (6).

$$V_{ref} = V_{S,EEDI} \cdot \left[\frac{P_{ME}}{P_{S,EEDI}}\right]^{\frac{1}{3}} \tag{5}$$

$$V_{ref} = k^{\frac{1}{3}} \cdot \left(\frac{DWT_{S,service}}{Capacity}\right)^{\frac{2}{9}} \cdot V_{S,service} \cdot \left[\frac{P_{ME}}{P_{S,service}}\right]^{\frac{1}{3}} \tag{6}$$

$V_{s,EEDI}$ is a service speed taken from sea-trails under the scantling draught. $P_{s,EEDI}$ is power of main engine that is matched to the service speed. Service power is equal to 85% of *MCR* and with no sea margin included. $DWT_{S,service}$ corresponds to deadweight, while $V_{S,service}$ is the sea-trial service speed under the design draught. $P_{S,service}$ is power of the main engine that matches the $V_{S,service}$ with no sea margin taken into account. Parameter k is the scale coefficient depending on the ship type and size. Furthermore, SFC_{ME} is obtained from the NOx technical file test report in case of 75% of *MCR* of the main engine, while SFC_{AE} is to be acquired from the same test report but for the auxiliary engine at 100% of power.

5. Results

In the following, the results are presented in a form of diagrams and include:

- *attained* vs. *required EEXI* evaluation (Fig. 4),
- difference between *attained* and *required EEXI* and EPL (Fig. 5),
- *MCR* reduction needed to comply with *EEXI* (Fig. 6).

Label "difference" is defined as a relative difference between *attained* and *required EEXI*, in percentages. Engine power limitation - EPL is the amount of main engine power reduction (in percentages) necessary in order to meet the *required EEXI*. When the relative difference is negative, the *attained EEXI* is lower than *required EEXI* and therefore, EPL is zero. Hence, there is no need for power reduction. *MCR* reduction (or MCR_{lim}) is new total power for which the *required EEXI* is satisfied.

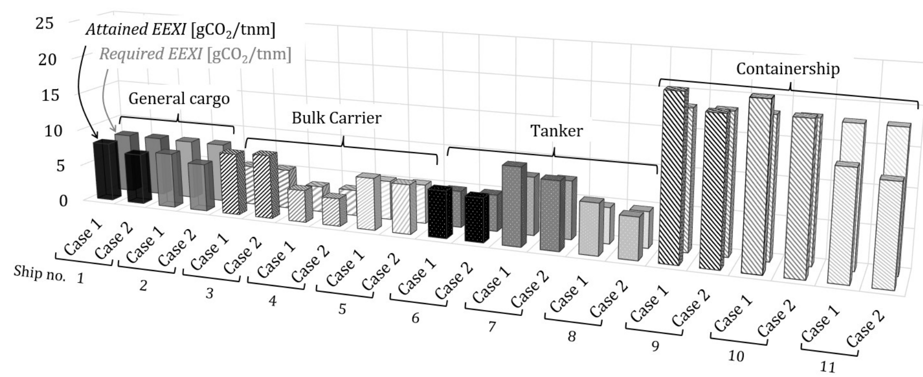

Fig. 4 – *Attained and required EEXI.*

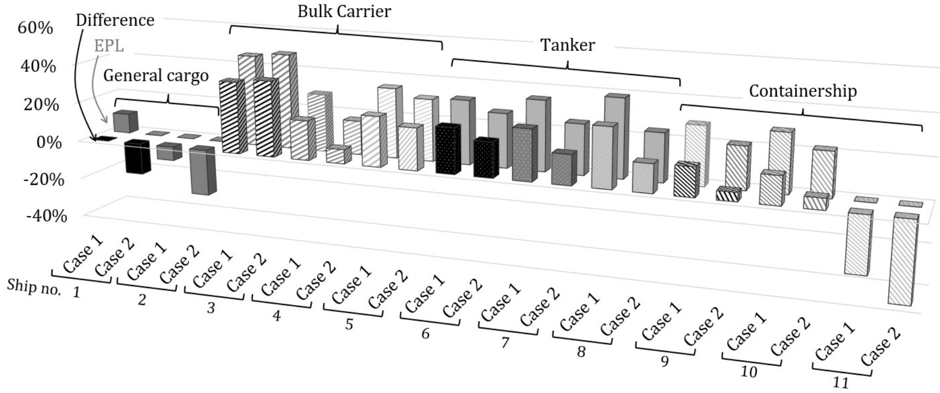

Fig. 5 – *Absolute and EPL power reduction.*

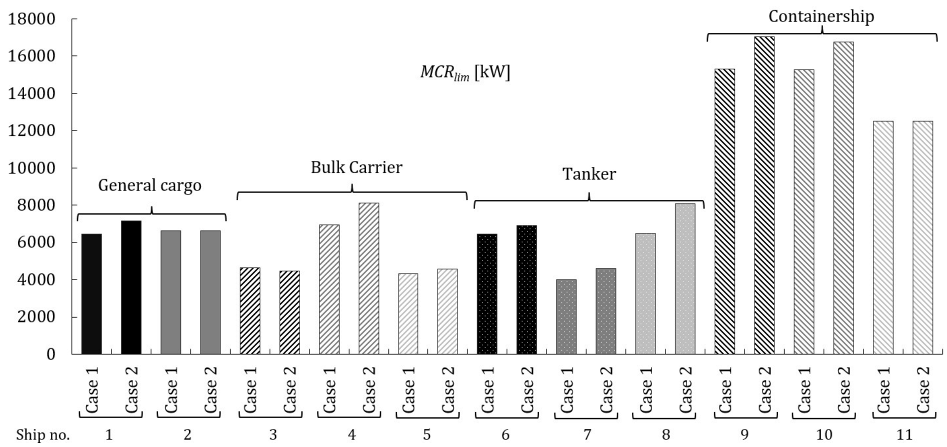

Fig. 6 – *MCR reduction.*

Study shows that 9 out of 11 ships are not satisfying present regulative in case 1, while 8 out of 11 are not passing the regulative in case 2, suggesting that those ships need energy efficiency improvement. However, depending on the input approach (case 1 vs. case 2) *attained EEXI* varies significantly, going from a few to more than 18%. This means that the same ship can satisfy the criterion using case 2 input approach and fall the criterion using case 1 approach (see the first general cargo ship in Fig. 4 and Fig. 5). Then again, if the same ship is not meeting the criterion in both input cases, the "margin" would not be the same so this could influence the future designer's choice on the application of energy saving devices. Consequently, EPL and *MCR* reduction necessary to meet the requirements differ between methods for the same ship. The total of 10 out of 11 ships have lower *attained EEXI* when case 2 is being applied. This means that the ship is more likely to meet the requirements when there is available sea-trial report and NOx technical file. Current calculation of energy efficiency and power reduction for existing ships vastly depends on obtained particulars and therefore, needs to be addressed in regulative.

Nevertheless, there are ways to decrease *attained EEXI*: for instance, the reduction of P_{ME} using mechanical or electronical engine power limiter in main engine, see Fig. 6. The second method could be the reduction of SFC_{ME} since such data are included in NOx technical files. Therefore, an actual data from main engine tests can be used instead of proposed statistical values and may lead to reduced *attained EEXI* value. Third method is to increase ship's capacity, i.e., deadweight for the same size. Moreover, one can increase reference speed by installing energy saving devices (ESD) such as: air lubrication, wind propulsion system, stern adjustments, etc.

An alternative fuel solution (such as LNG, methanol, hydrogen, biofuels, etc.) can also be used to reduce the emissions. They generally require larger storage and pose additional safety issues. Furthermore, propeller efficiency can be increased by more proper maintenance (cleaning, polishing, coating). Nonetheless, overall efficiency can be increased by implementing a variety of operational methods, for instance, operation planning in order to minimize the time spent on berth.

To end, although appears as trivial, a change of ship's class notation could result in reduction of *attained EEXI* since the procedures for its calculation slightly differs depending on the ship type. This possibility is applied and analyzed in the following section.

6. Class notation

As shown in Fig. 3, the criterion of *EEXI* for bulk carriers is stricter than for general cargo ships. Both classes are very similar in design characteristics and it is not unusual that a bulk carrier is classed as general cargo ship and vice versa. Here, authors investigated the effect of such "minor" change on energy efficiency of the same vessel.

6.1. *Inputs for the calculation*

Input parameters are determined according to case 1 and case 2 approach. Moreover, additional case no. 3 is defined as an optimal combination of input parameters (from case 1 and case 2 inputs) which can lead to the lowest *attained EEXI*. Case 3 assumes that the both statistical data and sea-trial reports are available and one can choose from which source shell obtain each parameter. The ship no. 3 has been chosen for this investigation, for which the statistical method (case 1) provided the lower *attained EEXI*. Input parameters are presented in Table 5.

Table 5 – *Input parameters.*

	Bulk carrier			General cargo ship		
Method	Case 1	Case 2	Case 3	Case 1	Case 2	Case 3
$SFC_{ME,APP}$	190.00	171.45	171.45	190.00	171.45	171.45
$SFC_{AE,APP}$	215.00	218.30	215.00	215.00	218.30	215.00
$V_{ref,avg}$	14.13	N/A	14.13	17.48	N/A	17.48
$V_{ref,app}$	14.59	N/A	14.59	14.46	N/A	14.46
V_{ref}	14.13	12.88	14.13	17.48	13.14	17.48
MCR_{avg}	6683	N/A	6683	12993	N/A	12993
MCR	8580	8580	8580	8580	8580	8580

6.2. *Effect of class notation change*

Effect of the class notation change of bulk carrier to general cargo ship is shown in Table 6.

Table 6 – *Results.*

	Bulk carrier			General cargo ship		
Method	Case 1	Case 2	Case 3	Case 1	Case 2	Case 3
Attained EEXI	8.371	8.633	7.611	8.445	8.462	7.678
Required EEXI	5.32			7.91		
Difference	36.42%	38.35%	30.07%	6.31%	6.50%	-3.04%
EPL	46%	48%	40%	16%	17%	0%
MCR_{lim}	4633	4462	5148	7207	7121	8580

Changing the class notation from bulk carrier to general cargo ship, according to the investigation presented in case of specific ship, can have a vast influence on the energy efficiency existing ship index. The main difference is addressed to the *required EEXI* since for the bulk carriers the proposed criterion is very strict. Therefore, the EPL could drop from 48% (the worst-case scenario) to 0% (the best-case scenario) for ship to meet the requirements by just changing the class notation. In this paper, the class change example is not considered as a measure for energy efficiency improvement. It is rather examined as a lack of current regulative to properly address the result variations due to this change.

7. Conclusion

IMO's most recent regulative on energy efficiency for already built ships is presented. Moreover, the energy efficiency is evaluated for the cargo fleet consisting of 11 ships that falls into the scope of four different classes: general cargo, bulk carrier, tanker and container ship. The performed analyses showed that 8 out of 11 ships are not satisfying the current regulative. For those ships a potential power reduction is calculated, with respect to the engine power limitation level and *MCR*, so that they can comply the criteria. Moreover, authors showed that different methods to determine input parameters can significantly affect the results. For instance, statistically obtained inputs led to two ships that met the requirements. Still, using sea-trail report data, energy efficiency was satisfied in case of three ships from the database. Moreover, 10 out of 11 ships have lower attained *EEXI*, if sea-trials are conducted and NOx technical file is available. Furthermore, possibilities for the reduction of *attained EEXI* are explored. One of those, a class notation change from bulk carrier to general cargo, showed that such change has a significant influence on *EEXI*.

The paper showed that the present regulative based calculation of energy efficiency of existing ships is very sensitive to input methods and class notation. Regulations have impact on ship design. However, most of the solutions to improve energy efficiency are still related to reduction of speed and power.

8. Acknowledgments

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Nomenclature

B – Breadth [m];
$Capacity$ – equals to DWT at scantling draught, except for containerships where it is equal to $0.7DWT$ [t];
C_{FAE}, C_{FME} – Conversion factor between fuel consumption and CO_2 emission for auxiliary and main engine [$tCO_2/tFuel$];
D – Depth [m];
EEDI – energy efficiency design index (*attained EEDI*, *required EEDI*) [gCO_2,/tnm]
EEXI - energy efficiency existing ship index (*attained EEXI*, *required EEXI*) [gCO_2,/tnm]
f_c – Cubic capacity correction factor [/];
f_i – Capacity correction factor [/];
f_l – Factor for general cargo ships equipped with cranes and other cargo-related gear [/];
f_m – Factor for ice-classed ships having IA Super and IA [/];
f_w – Factor for speed reduction at sea [/];
$DWT_{design}, DWT_{S,service}, DWT_{scantling}$ – Deadweight at design, service, scantling draught [t];

k – Scale coefficient [/];
L_{oa}, L_{pp}– Length overall, between perpendiculars [m];
LWT – Lightweight [t];
MCR – Maximum continuous rating (maximum power of main engine) [kW];
MCR_{lim} – Maximum continuous rating after installing EPL [kW];
m_v – performance margin [kn];
P_{AE} – Power of auxiliary engine [kW];
$P_{AE,eff}$,P_{eff} – Innovative mechanical energy efficient technology for auxiliary and main engine [kW];
P_{ME}, P_{PTI} – Power of main and shaft engine [kW];
$P_{S,EEDI}$, $P_{S,service}$ – Power of main engine corresponding to $V_{S,EEDI}$, $V_{S,service}$ [kW];
$SFC_{ME,}$ SFC_{AE}– Specific fuel oil consumption for main engine and auxiliary engine [g/kWh];
$SFC_{ME,app,}$$SFC_{AE,app}$ – Approximated specific fuel oil consumption for main and auxiliary engine [g/kWh];
$T_{design,}$$T_{scantling}$ – Design, scantling draught [m];
V_{design} – Design speed [kn]
$V_{ref,}$ $V_{ref,avg,}$$V_{ref,app}$ – Reference speed, average reference speed, approximated reference speed [kn];
$V_{S,EEDI,}$ $V_{S,service}$ – Sea trial service speed under the *EEDI* and design load draught [kn];
Y – Reduction factor [-];
$\Delta_{scantling}$ – Displacement at scantling draught [m^3].

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Kalajdžić Milan
University of Belgrade,
Faculty of Mechanical Engineering,
Department of Naval Architecture,
Kraljice Marije 16, Belgrade, Serbia,
Email: mdkalajdzic@mas.bg.ac.rs

Vasilev Matija
Ocean Pro Marine Engineers Ltd.,
Golsvordijeva 1, Belgrade, Serbia
Email: matija@oceanpro.eu

Momčilović Nikola
University of Belgrade,
Faculty of Mechanical Engineering,
Department of Naval Architecture,
Kraljice Marije 16, Belgrade, Serbia,
Email: nmomcilovic@mas.bg.ac.rs