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Optimization of Sea Buses in Turkey in terms of Energy Efficiency Design Index (EEDI)

Aydin Tokuslu[1*]

[1] Turkish Naval Forces, Ankara, Turkey

E-Mail: *aydintokuslu78@gmail.com*
Orcid:0000-0002-5851-6902

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Abstract: Energy efficiency in ships has been extensively studied and many applicable solutions have been found in the literature. The Energy Efficiency Design Index, which aims to reduce the CO_2 emissions of ships is valid for international merchant ships of 400 gross tonnage and above and ships with a construction contract on or after January 01, 2013. This implementation became a fast key instrument for the ships to be energy efficient. In this study, the energy efficiency of 21 sea buses operating in Istanbul Strait was analysed. The energy efficiency design index of sea buses was estimated and investigated whether there is a need for optimization in light of EEDI for non-energy efficient ships. Some practical measures have been offered to reduce EEDI value and the harmful effects of CO_2 exhaust gas emission.
Keywords: EEDI, Ship, Energy, Efficiency, IMO, Optimization

INTRODUCTION

Maritime transport remains the foundation of the global trade and manufacturing supply chain, as more than four-fifths of the world's goods trade is transported by sea. Volumes of goods increased by 2.7 percent, below the historical average of 3.0 percent from 1970-2017 and 4.1 percent in 2017. However, they reached a milestone in 2018 when total volumes reached a height of 11 billion tons for the first time on the UNCTAD record [1]. Dry bulk, followed by container, tanker, gas, and chemical vessels are the most contributing ship types in the growth of international maritime trade. These are the types of ships that cause the most emissions of global emissions, and the emissions generated by these ships increase in parallel with the volume of trade. The International Maritime Organization has introduced new measures to reduce anthropogenic emissions from commercial vessels. One of these measures is the Energy Efficiency Design Index, which aims to reduce the CO_2 emissions of ships [2,3]. The regulations on the energy efficiency of ships are valid for international merchant ships of 400 gross tonnages and above and ships with a construction contract on or after January 01, 2013. With this regulation, it is aimed to make new ships more energy-efficient and to put technical measures and new systems (engines, propellers, etc.) for newly designed ships. EEDI stipulates minimum energy use and CO_2 emissions per unit load per ton/mile for different ship types and models from the design stage [4]. The lower the EEDI of the ship, the more energy-efficient the ship is and the less CO_2 emissions it emits. EEDI did not intend to use the current merchant fleet's energy efficiency as a performance indicator.

Energy efficiency in ships has been extensively studied and many applicable solutions have been found and presented in the literature. Literature studies show that all of these measures are feasible. Karim and Hasan [5] analysed the inland vessels of Bangladeshi concerning EEDI and found that the inland vessels are not energy efficient, and need optimization. Zakaria and Rahman [6] examined the inland cargo vessels of Bangladesh which has been based on 351 existing vessels. They improved the EEDI for seagoing vessels due to the limitation of carrying capacity and installed main engine power. Some applicable measures were proposed to be implemented for the new ships. Tien [7] estimated the EEDI in the field of ship energy efficiency for the bulk carrier with ship name M/V Jules Garnier and demonstrated measures to increase ship energy efficiency. Simić [8] investigated the inland waterway self-propelled cargo ships and proposed a reliable tool for benchmarking energy efficiency and modified energy efficiency design index for these self-propelled cargo ships. Tokuslu [9] studied one of the container ships of the Turkish maritime trade fleet in terms of energy efficiency performance. The ship`s

[*]*Corresponding E-mail: aydintokuslu78@gmail.com*

energy efficiency was found as an energy-efficient. Some practical proposals have been presented to improve the ship`s energy efficiency in the short, medium, and long term.

In general, all of these literature studies have focused on the energy efficiency of existing and new ships and demonstrate the importance of the research needed to implement IMO's regulations on reducing greenhouse gas emissions from ships. In this study, the energy efficiency of 21 sea buses operating in Istanbul Strait was analysed. No study to date has examined the energy efficiency of sea buses. The energy efficiency design index of sea buses was estimated and investigated whether there is a need for optimization in light of EEDI for non-energy efficient ships. This study will give us an opinion on how the ships can be more energy efficient by making some simple steps.

METHODOLOGY

The EEDI implementation covers the designated types of ships, which have the largest and most fuel consumption of the shipping and aims to make 72% of the merchant fleet energy efficient. Ships with diesel, electric, steam, and hybrid propulsion systems are not included in this implementation. Ship types to which EEDI will be applied;

a. Oil tankers,
b. Bulk carriers,
c. Gas carriers,
d. General cargo,
e. Container ships,
f. Refrigerated cargo,
g. Combination carriers,
h. Roro cargo ship,
i. Roro passenger ship,
j. Cruise passenger ship [10].

As of January 01, 2013, EEDI implementations have been started and energy efficiency plans have been made every 5 years depending on the technologies that will develop in this field. The EEDI implementation schedule is shown in Figure 1 [11]. Energy efficiency is foreseen as 10% in the first phase and it is aimed to increase it to 30% by 2030. This ratio is expected to increase to 50% by 2050.

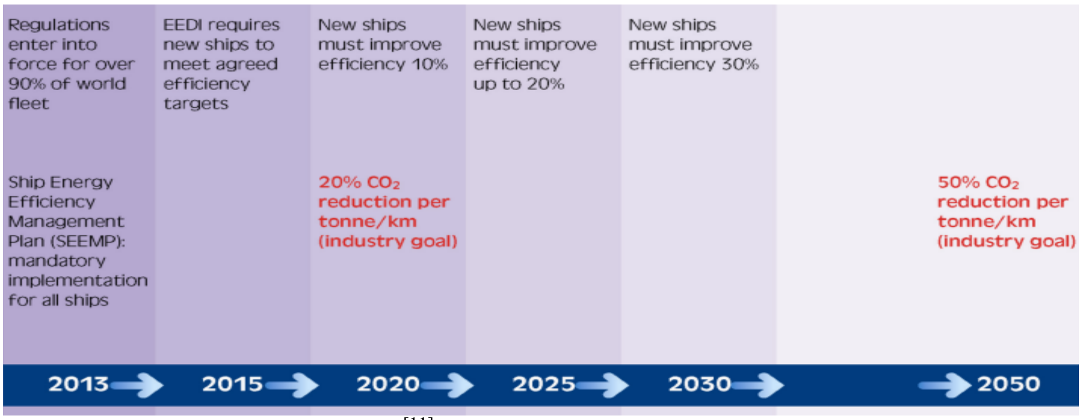

Figure 1. EEDI implementation schedule [11]

Calculation Method

EEDI calculation module was included in Marpol Annex VI with the directive MEPC.1 / Circ.681 at the MEPC meeting held by IMO in 2011 and it has been put into effect as of January 01, 2013. The EEDI Equation (1,2)[4] consists of the following equation;

$$EEDI_{attained} = \frac{CO_2 Emission}{Transport\ work} \qquad \text{(Equation 1)[4]}$$

$$EEDI_{attained} = \frac{(P\ (ME) * SFC\ (ME) * Cf(ME)) + (P(AE) * SFC\ (AE) * Cf(AE))}{Capacity * Vref} \quad \text{(Equation 2)[4]}$$

P_{ME} : The power of the main engine in kW
P_{AE} : The power of the auxiliary engine in kW
$SFC_{ME,\ AE}$: Fuel consumption burned by the main and auxiliary engine in kW
C_{fME}, C_{fAE} : Emission rate of fuel used by the ship (presented in Table 1)
Capacity : Ship's tonnage (in tons)
Vref : Design speed of the ship (in knots)

Table 1. Carbon content and C_F values of different types of fuel [12]

Type of fuel	Reference	Carbon Content	C_F (t-CO_2/t-Fuel)
Diesel / Gas Oil	ISO 8217 Grades DMX through DMB	0.8744	3.206
Light Fuel Oil (LFO)	ISO 8217 Grades RMA through RMD	0.8594	3.151
Heavy Fuel Oil (HFO)	ISO 8217 Grades RME through RMK	0.8493	3.114
Liquefied Petroleum Gas (LPG)	Propane	0.8182	3.000
	Butane	0.8264	3.030
Liquefied Natural Gas (LNG)		0.7500	2.750
Methanol		0.3750	1.375
Ethanol		0.5217	1.913

The comprehensive descriptions of the EEDI formula are presented are at IMO MEPC Resolution 245 (66) [12] which contains different constants and coefficients. When we estimated the EEDI according to this equation (1,2) for the target ship, the attained EEDI can be found. The reference EEDI must be bigger than the attained EEDI, if the reference EEDI doesn`t surpass the attained EEDI, the ship is considered energy efficient. we can estimate the reference EEDI (Equation 3) with the formula stated below;

$$\text{The reference EEDI} = a \times b^{-c} \quad \text{(Equation 3)}$$

Reference line value (a, b, and c) parameters are shown in Table 2. The reference line values are provided from the vessel database of Lloyd's Register Fair play. Sample reference lines for ship types are shown in Figure 2 which was created from Lloyd's Register Fair play database [4].

Table 2. Reference line value (a, b, and c) parameters (the reference EEDI)[4]

Ship type defined in regulation	a	b	c
Bulk carrier	961.79	DWT	0.477
Gas tanker	1120	DWT	0.456
Tanker	1218.8	DWT	0.488
Container ship	186.52	DWT	0.200
General cargo ship	107.48	DWT	0.216
Refrigerated cargo carrier	227.01	DWT	0.244
Combination carrier	1219	DWT	0.488
Roro cargo ship	1405.15	DWT	0.5
Roro passenger ship	752.16	DWT	0.38
LNG carrier	2253.7	DWT	0.47
Cruise passenger ship having non-conventional propulsion	170.84	GRT	0.21

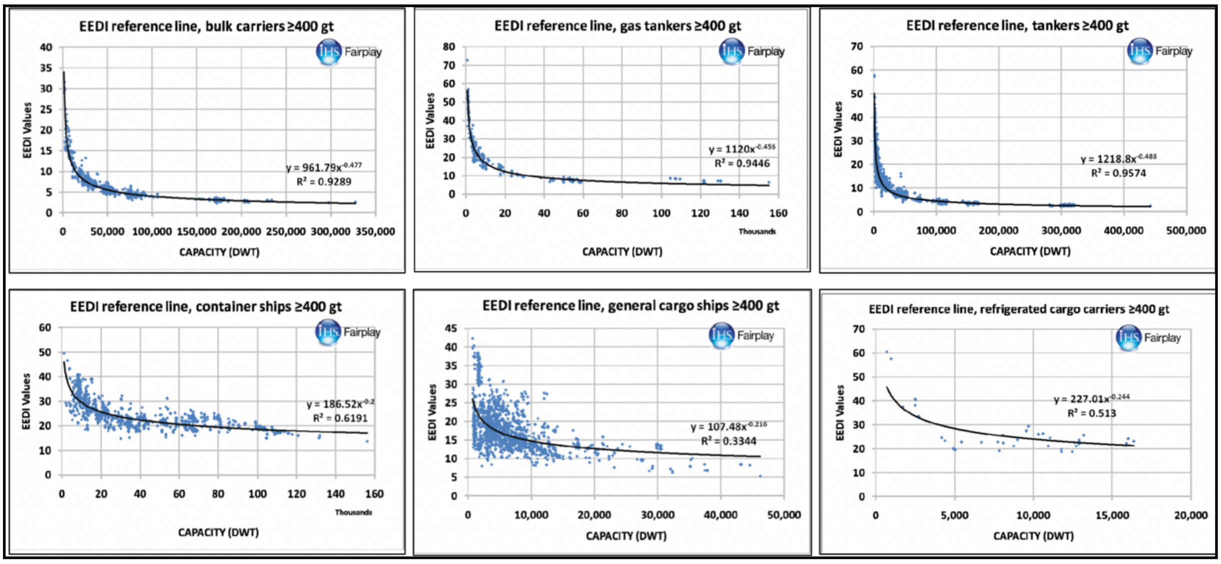

Figure 2. Sample reference lines for ship types developed by the IMO [13]

Table 3 demonstrates the EEDI reduction factors and cut off limits through implementation phases. EEDI reduction factors and cut off limits will help us to calculate the required EEDI based on the year of the ship built. The required EEDI must be bigger than the attained EEDI (the attained EEDI ≤ the required EEDI).

Table 3. EEDI reduction factors and cut off limits through implementation phases [2]

Ship Type	Size	Phase 0 1 Jan 2013-31 Dec 2014	Phase 1 1 Jan 2015-31 Dec 2019	Phase 2 1 Jan 2020-31 Dec 2024	Phase 3 1 Jan 2025 and onwards
Bulk Carrier	20.000 DWT and above	0	10	20	30
	10.000 DWT and above	n/a	0-10*	0-20*	0-30*
Gas Carrier	10.000 DWT and above	0	10	20	30
	2.000-10.000 DWT	n/a	0-10*	0-20*	0-30*
Tanker	20.000 DWT and above	0	10	20	30
	4.000-20.000 DWT	n/a	0-10*	0-20*	0-30*
Container Ship	15.000 DWT and above	0	10	20	30
	10.000-15.000 DWT	n/a	0-10*	0-20*	0-30*
General Cargo Ships	15.000 DWT and above	0	10	20	30
	3.000-15.000 DWT	n/a	0-10*	0-20*	0-30*
Ro-Ro Cargo Ships***	2.000 DWT and above	n/a	5**	20	30
	1.000-2.000 DWT	n/a	0-5*,**	0-20*	0-30*
Ro-Ro Passenger Ships***	1.000 DWT and above	n/a	5**	20	30
	250-1.000 DWT	n/a	0-5*,**	0-20*	0-30*

Note: n/a means no required EEDI applies

* Reduction factor is linerally interpolated between the two values depending on the size of the ship
** Phase 1 is applied to all ships on September, 1st 2015
*** Reduction factor is applied to all ships after September, 1st 2019

Ship particulars

Sea buses are used for passenger and vehicle transportation in Istanbul Strait and the Marmara Sea. In this study, the energy efficiency of 21 sea buses operating in Istanbul Strait was examined. Detailed information about ships (tonnage, machine power, speed, height/width ratio, etc.) is presented in Tokuslu [14].

EEDI OF SEA BUSES

21 sea buses in the Istanbul Strait have been taken into consideration and based on the acquired data, the reference EEDI and the attained EEDI of the ship were calculated using equation 1 and 2 as per IMO guideline (Table 4). The reference line value for the sea buses was displayed in Figure 3. This reference line was created by Erat [15]. Reference line value (reference EEDI) of a: 226,37 and c: 0,172. For example, when we calculated the reference EEDI of Mehmet Reis-11 (first ship in the Table 4), = a × b^{-c} = 226,37 x $644^{-0,172}$ = 74,420 (gCO_2/ton.mile). Therefore, the ship must be designed not to emit 74.420 (gCO_2/ton.mile) to be considered energy efficient. Reference EEDI calculations of other sea buses are performed as in the above example.

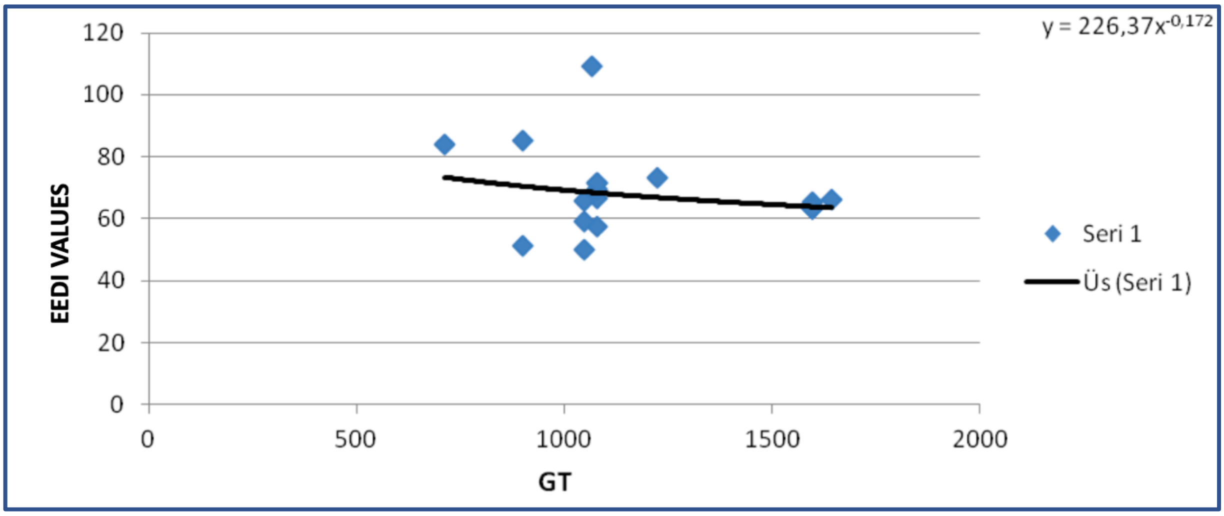

Figure 3. Reference line value for the sea buses [15]

For sea buses, 75% of their main engine power is used in the calculation of P(ME) [16, 17]. The main engine power (P(ME)) for Mehmet Reis-11 understudy was calculated as 1.830 kW. In addition to main engine power, auxiliary engine power (P(AE)) is also involved in the calculation. Auxiliary engine power is calculated as (P(AE) = (0.025 X main engine power) + 250) if the main engine power is ≥ 10.000 kW. Auxiliary engine power (P(AE) is calculated as (0.05 x main engine power)) if the main engine power is < 10.000 kW [16,17]. According to this calculation, since the main engine power of the target ship (Mehmet Reis-11) is less than 10.000 kW, the auxiliary engine power (P (AE)) is calculated as 122 kW. To save fuel, the fuel used by the ship is diesel (MDO), and the emission factor was found to be C_F 3.206 from Table 1 [10]. The daily fuel consumption of diesel fuel by the main engine (SFC (ME)) is 165 kW, and the daily fuel consumption of the auxiliary engine (SFC (AE)) is 220 kW [10]. The attained EEDI is estimated according to equation 1,2 with the data we have. Calculation of the attained EEDI of Mehmet Reis-11 (first ship in Table 4);

$$EEDI_{attained} = \frac{(P\ (ME) * SFC\ (ME) * Cf(ME)) + (P(AE) * SFC\ (AE) * Cf(AE))}{DWT * Vref} = \frac{(1830 * 165 * 3{,}206) + (122 * 220 * 3{,}206)}{644 * 30{,}9}$$

= 52,97 (gCO_2/ton.mile)[11, 12, 13]

Since the reference EEDI is bigger than the attained EEDI, this ship can be considered as an energy-efficient ship. This vessel doesn`t exceed its EEDI value and doesn`t need the optimization. The attained

EEDI estimations of other sea buses are performed as in the below example. In the EEDI calculation (attained and reference) for all sea buses, there are different EEDI values due to the characteristics (dimension, capacity, speed, and other hydrodynamic properties) of all ships. According to the characteristic features of ships, some ships have emerged as energy-efficient and some as energy inefficient. Energy-efficient ships are shown in green colour, non-energy efficient ships that need optimization are shown in red colour (Table 4). It was revealed by the analysis that 76% of the sea buses were not energy efficient. After implementing EEDI reduction measures, the attained EEDI will be less than the reference EEDI and the non-energy efficient ships will be considered as an energy-efficient ship. The non-energy efficient ships require to be optimized in terms of EEDI to increase energy efficiency. Energy efficiency analyses should be carried out while the ship is still in the design stage and it should be aimed to be more energy efficient. Energy efficiency applications that will be performed after the ship starts cruising will not have a permanent benefit, so EEDI applications are mandatory in the design stage for all ships.

Table 4. Estimation of attained and reference EEDI of sea buses in Turkey

Vessel name	Built Year	L WL (m)	B MLD (m)	L/B	T (m)	B/T	GRT	Speed (knots)	ME (kW)	EEDI attained	reference EEDI
Mehmet Reis-11	2007	42,9	12,4	3,459	2,7	1,281	644	30.9	2440	52,97	74,420
Murat Reis-7	2007	42,9	12,4	3,459	2,7	1,281	644	30.9	2440	52,97	74,420
Umur Bey	1987	38,8	9,44	4,110	2,45	1,678	431	32	2440	76,428	79,742
Temel Reis-2	1997	35	10	3,50	1,96	1,786	395	32	2440	83,394	80,948
Hızır Reis-3	1998	35	10	3,50	1,96	1,786	395	32	2440	83,394	80,948
Sokullu M. Paşa	2000	35	10	3,50	1,96	1,786	395	32	2440	83,394	80,948
Barbaros H. Paşa	2000	35	10	3,50	1,96	1,786	395	32	2440	83,394	80,948
Piyale Paşa	1996	38,8	10,5	3,695	1,3	2,842	395	34	2440	78,489	80,948
Sinan Paşa	1996	38,8	10,5	3,695	1,3	2,842	395	34	2440	78,489	80,948
Eskihisar-1	1986	80,71	22	3,668	4,5	0,815	1596	11	3044	74,905	63,665
Halıdere	1987	80,71	22	3,668	4,5	0,815	1596	11	3044	74,905	63,665
Hereke-3	1986	80,71	22	3,668	4,5	0,815	1596	11	3044	74,905	63,665
Karamürsel	1986	80,71	22	3,668	4,5	0,815	1596	11	3044	74,905	63,665
Kaptan Ş. Göğen	1988	80,71	22	3,668	4,5	0,815	1596	11	3044	74,905	63,665
Topçular-1	1986	80,71	22	3,668	4,5	0,815	1596	11	3044	74,905	63,665
Gayrettepe	1989	67,24	20,5	3,28	4,5	0,728	1905	11	3044	62,755	61,756
Galatasaray	1989	67,24	20,5	3,28	4,5	0,728	1905	11	3044	62,755	61,756
Okmeydanı	1989	67,24	20,5	3,28	4,5	0,728	1905	11	3044	62,755	61,756
Topkapı	1970	67,24	20	3,362	4,1	0,82	1905	11	3044	62,755	61,756
Zeytinburnu	1987	67,24	20,5	3,28	4,5	0,728	1905	11	3044	62,755	61,756
Bozcaada	1989	67,24	20	3,362	4,1	0,82	1905	11	3044	62,755	61,756

RESULTS AND DISCUSSION

It can be seen from Table 4 that small ships are having higher EEDI (attained and reference) values when compared to bigger ships and small ships emit higher CO_2. This doesn`t mean that IMO is advising to design bigger ships since we know that the bigger ships are more transport efficient than small ones. In this case, we can expect that every ship has a different hydrodynamic characteristic which can make it more energy-efficient. The non-energy efficient ships require to be optimized in terms of EEDI to increase energy efficiency. To make non-energy efficient ship energy efficient, one of the inefficient ships (Temel Reis-2) (fourth ship in Table 4) were taken under consideration. The reference EEDI of Temel Reis-2 is = $a \times b^{-c}$ = 226,37 x $395^{-0,172}$ = 80,948 (gCO_2/ton.mile). Therefore, the ship must be designed not to emit 80.948 (gCO_2/ton.mile) to be considered energy efficient. And attained EEDI of this ship is = 83.394. After optimization, the attained EEDI must be less than the reference EEDI. Optimization of ship`s length, breadth, and speed are shown in Table 5,6,7.

From Table 5, it has been found that attained EEDI decreases as the length increases without changing the transport capacity and at higher speed, lengthier ships perform well.

From Table 6, it has been detected that attained EEDI decreases as the breadth increases at 32-knot speed. Main engine power (ME) decreases with the increase of breadth.

From Table 7, it has been observed that attained EEDI decreases with the decrease of speed and this means that speed reduction gives a better performance in terms of EEDI, the ship becomes more energy efficient and the ship emits less CO_2 emission. The ship definitely must navigate with the speed of 24-26 knots which are the economic speed. Main engine power (ME) increases with an increase in speed. A study conducted by Mersin [18] also showed that fuel consumption and CO_2 emissions significantly decreased by reducing the speed of the ship to speeds of 5, 6, 7, 8 knots.

With this optimization study, it was found that attained EEDI can be reduced by 20-30% by changing the appropriate characteristics of the ship. This optimization study can also be done for other non-energy efficient sea buses. Optimization studies have shown a good result in improving the energy efficiency of sea buses.

Table 5. Optimization of ship`s length with respect to EEDI (sea buses)

Situation	Length (m)	Breadth (m)	Draft (m)	Cb	GRT	ME (kW)	Speed (knots)	Attained EEDI	Reference EEDI
Origin	35	10	1,96	0,85	395	2440	32	83,394	80,948
5% less	33,25	10,27	1,96	0,85	395	2543	32	86,914	80,948
10% less	31,5	11,11	1,96	0,85	395	2663	32	91,016	80,948
5% more	36,75	9,52	1,96	0,85	395	2378	32	81,275	80,948
10% more	38,5	9,09	1,96	0,85	395	2337	32	79,874	80,948

Table 6. Optimization of ship`s breadth with respect to EEDI (sea buses)

Situation	Length (m)	Breadth (m)	Draft (m)	Cb	GRT	ME (kW)	Speed (knots)	Attained EEDI	Reference EEDI
Origin	35	10	1,96	0,85	395	2440	32	83,394	80,948
5% less	36,8	10,5	1,96	0,85	395	2374	32	81,138	80,948
10% less	38,89	11	1,96	0,85	395	2327	32	79,532	80,948
5% more	33,34	9,5	1,96	0,85	395	2537	32	86,709	80,948
10% more	31,82	9	1,96	0,85	395	2641	32	90,264	80,948

Table 7. Optimization of ship`s speed with respect to EEDI (sea buses)

Situation	Length (m)	Breadth (m)	Draft (m)	Cb	GRT	ME (kW)	Speed (knots)	Attained EEDI	Reference EEDI
Origin	35	10	1,96	0,85	395	2440	32	83,394	80,948
5% less	35	10	1,96	0,85	395	2093	30	76,303	80,948
10% less	35	10	1,96	0,85	395	1758	28	68,668	80,948
15% less	35	10	1,96	0,85	395	1499	26	63,056	80,948
20% less	35	10	1,96	0,85	395	1275	24	58,102	80,948

CONCLUSIONS

In this study, sea buses were examined in terms of EEDI performance and we reached the result that 76% of the sea buses were not energy efficient. However, the sea buses were built between 1970 and 2007 and not under the mandatory regulation of MARPOL EEDI, but EEDI reduction measures can be implemented to become energy efficient. After implementing, the attained EEDI will be less than the reference EEDI and the non-energy efficient ships will be energy efficient. From this study, subsequent results can be obtained:

- One of the most important reasons for the low attained EEDI of non-energy efficient ships is the inappropriate engine selection.

- A relatively lengthier ships perform well in terms of EEDI. A slim hull form is appropriate, which will create a smaller pressure difference between bow and stern.
- Speed reduction gives a better performance in terms of EEDI, the ship becomes more energy efficient and the ship emits less CO_2 emission. The ship definitely must navigate with the speed of 24-26 knots which are the economic speed.
- Instead of diesel fuel oil, alternative fuels such as LNG, LPG, gas oil can be used which makes a 3/4% reduction in EEDI performance.

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