Bayraktar, M and Yüksel, O

Investigation of the effect of anti-fouling systems on meeting energy efficiency regulations

http://researchonline.ljmu.ac.uk/id/eprint/24546/

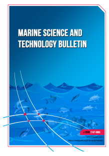
Article

Citation (please note it is advisable to refer to the publisher's version if you intend to cite from this work)

Bayraktar, M and Yüksel, O (2023) Investigation of the effect of anti-fouling systems on meeting energy efficiency regulations. Marine Science and Technology Bulletin, 12 (2). pp. 172-181.

Mar. Sci. Tech. Bull. (2023) 12(2): 172-181
e–ISSN: 2147–9666
info@masteb.com

dergipark.org.tr/en/pub/masteb
www.masteb.com
DOI: 10.33714/masteb.1276367



Marine Science and Technology Bulletin

PRENSIP
https://prensip.gen.tr/

RESEARCH ARTICLE

Investigation of the effect of anti-fouling systems on meeting energy efficiency regulations

Murat Bayraktar[1] • Onur Yüksel[1]*

[1] *Zonguldak Bülent Ecevit University, Maritime Faculty, Marine Engineering Department 67300, Zonguldak, Türkiye*

ARTICLE INFO

Article History:
Received: 03.04.2023
Received in revised form: 31.05.2023
Accepted: 02.04.2023
Available online: 20.06.2023

Keywords:
Anti-fouling
Biofouling
CII
CII rating and EEXI
Frictional resistance

ABSTRACT

The operational efficiency of marine vessels should be kept as high as possible to achieve sustainable development goals in the maritime field. However, a lot of factors such as resistance components reduce the operational efficiency of the ship. Frictional resistance is the biggest resistance component for the power needed on ships and its coefficient increases due to the biofouling as long as the ship interacts with seawater. The increased total resistance of the ship causes extra power needed and excessive fuel consumption to reach service speed. The increase in both fuel consumption and power will create an obstacle to meeting the EEXI and CII reference values which became mandatory after January 1, 2023. That's why the utilization of effective anti-fouling systems is quite critical in maritime applications. The purpose of this study is to reveal anti-fouling systems' effect on EEXI, CII, and CII ratings by utilization of the container ship operated in liner shipping. That's why, high, medium, and low effective anti-fouling system scenarios have been created since the effect of each anti-fouling will not be the same on the container ship. According to the results, the required EEXI and CII reference values will have been met respectively when the effect of ship biofouling is ignored. However, the reduction ratios and biofouling effect have created quite a challenge in meeting EEXI and CII in the following years. Although the required EEXI value has been met for 2024 and 2025 by the high-effective anti-fouling system and reference value has not been met by the low-effective anti-fouling system in the following years. Any anti-fouling system utilized in this paper won't be sufficient to meet the reference value at the end of 2023 because attained CII of the container ship is very close to the reference value of CII in 2023. The CII rating of the container ship will have been at C level until the end of 2026 when the biofouling effect is ignored. However, it decreased to D and E levels in the following two years depending on the best and worst scenarios. This study will be a valuable resource for scientists, researchers, experts, and maritime stakeholders who want to investigate the effect of EEXI, CII, and CII rating of antifouling systems.

Please cite this paper as follows:

Bayraktar, M., & Yüksel, O. (2023). Investigation of the effect of anti-fouling systems on meeting energy efficiency regulations. *Marine Science and Technology Bulletin*, *12*(2), 172-181. https://doi.org/10.33714/masteb.1276367

---

* Corresponding author
E-mail address: onur.yuksel@beun.edu.tr (O. Yüksel)

Introduction

International Maritime Organization (IMO) works to reduce marine pollution originating from ships as much as possible to ensure sustainable development goals (IMO, 2023a) since more than 80% of global transportation is carried out by maritime transportation (UNCTAD, 2023). Biofouling is one of the obstacles to realizing sustainable and efficient operations in maritime transportation. Biofouling occurs when aquatic organisms growing quite rapidly attach to the ship's hull or are contained in ballast water (Levin, 2013). The first organic molecule initiates attaching to the ship hull in one minute as soon as the ship's hull submerges into the water and starts the fouling process. Growing aquatic organisms have simply been transferred from one region to another utilizing large-scale maritime transportation. Aquatic organisms in one area can be invasive to transferred local areas and they result in the degradation of aquatic life and biodiversity (Davidson et al., 2016; IMO, 2023b). The ever-developing maritime trade has triggered the effect of biofouling and that's why the Marine Environment Protection Committee (MEPC) took a decisive step and published a guideline for the control and management of ships' biofouling to minimize the transfer of invasive aquatic species (IMO, 2003) as well as researchers, managers, and policymakers have highly concerned translocated invasive organisms (Davidson et al., 2016). Many coating, paint, surface treatment, or device systems have been utilized to prevent unwanted organisms that have the potential to attach to the ship's hull (Wartsila, 2023). Lime and arsenic were used in early ship operations and then tributylamine (TBT) which was the most well-known antifouling painting in modern times had been utilized to protect biofouling. however, studies revealed that tributyltin has highly poisonous effects on sea life and causes irreversible damage to the environment and economy. That's why the International Convention on the Control of Harmful Anti-Fouling Systems on Ships (AFS Convention) has been adopted to ban the use of harmful organisms in antifouling systems by IMO (IMO, 2003). Moreover, the utilization of Cybutryne in anti-fouling systems has been banned as of January 1, 2023 (DNV, 2022).

On the other hand, biofouling especially occurred in ship hulls has also adversely affected the ship's hydrodynamic performance due to creating additional resistance (IMO, 2003). More power is needed to reach service speed in the fouled hull compared to the clean hull (IMO, 2023b). Small-scale ship hull fouling leads to increases of up to 40% in fuel consumption, and even this rate reaches 50% depending on the vessel speed (IMO, 2003; IMO, 2023b).

The age and condition of the ship utilized anti-fouling coating systems, service speed, water temperature as well as operation profile which refers frequency of idling, transit, and maneuvering are critical factors in the growth of biofouling. Moreover, prolongation of the ship's spending time at anchor accelerates the growth rate. Rudder, propellers, and propeller shafts are among the most susceptible areas to biofouling. The frequency of anti-fouling coating system maintenance intervals postpones the formation of fouling as much as possible (IMO, 2012).

The propulsion dynamics effects of hull fouling are one of the primary concerns in the maritime sector (Davidson et al., 2016). A ship with clean hull cruises more with less power because friction resistance, which is one of the biggest resistance components on the ship, is minimized (IMO, 2003). Extra power needed increases fuel consumption and fuel-based emissions in the ship operations with the fouled hull (IMO, 2023b). In addition to the adverse effect on the ship's performance, fouling increases the formation of corrosion and causes clogging of the necessary water inlets for the emergency fire pump, scrubber system, sea chest, and more (IMO, 2012).

One of the sustainable development goals is climate action since global warming has constantly been increasing which will have devastating consequences such as flooding, drought, poverty, inability to fundamental needs, and more. The increase in global warming is 1.1°C above the pre-industrial period which is the highest increment experienced in recent years. Almost a quarter of global energy-related CO_2 emissions are caused by transport and approximately 2% of the energy-related CO_2 emissions are attributable to international shipping (IEA, 2009; United Nations, 2023).

The IMO under the GHG strategies aims to reduce carbon emissions by 40% and 70% rates by 2030 and 2050, respectively compared to 2008 (IMO, 2023c). IMO has announced the energy efficiency existing index (EEXI) and carbon intensity indicator (CII) ratings to reduce the CO_2 emission from ships (Bayraktar & Yüksel, 2023; Konur et al., 2023). These metrics require the efficient operation of marine vessels to lower the fuel consumption of the vessel. Decreased performance of the vessel due to the fouling can cause it not to meet these requirements. EEXI has been created under the greenhouse gases (GHG) emission reduction strategy to increase the energy efficiency of ships step by step. Ships above the EEXI reference line will have been out of service over time.

This study examines the effect of the fouling by employing various fouling factors on a reference container vessel to observe the fuel consumption increase. The impact of the increased fuel consumption on the EEXI, CII, and CII ratings have been examined and discussed. The paper structure consists of literature review, research gap and contribution, methodology, results and discussion, and conclusion sections.

Literature Review

The main purpose of antifouling systems is to minimize the impact of the settlement of fouling species on drag resistance as much as possible (Munk et al., 2009). Various fouling prevention systems have been utilized and investigated in research papers. Turan et al. (2016) investigated the fouling effect on the LNG tanker by using three plates that have different frictional resistance coefficients. Artificial barnacles have been utilized on plates with 5%, 10%, and 20% coverage to create frictional resistance. The frictional resistance coefficient has doubled in the third plate corresponding to 20% coverage and substantial drag characteristics have been experienced on the remaining plates. Needed effective power has increased by 22.5%, 41.3%, and 59.7%, respectively, due to plates covered with artificial barnacles compare to operations of the LNG tanker with a clean hull at speeds of 20 knots. Performance reduction rate may differ in real ship applications since artificial barnacles have homogeneously been distributed on the plate. Hakim et al. (2017) have conducted towing test to explore the marine fouling effect using sandpapers that have different roughness values. Ship hull having irregular roughness has caused a 41.88% resistance increment to compare the smooth ship hull model. Hakim et al. (2017) recorded the full consumption rate of ferries throughout 11 months after dry-docking. The fuel consumption rate increased by 20% at the end of the period due to fouling.

Hakim et al. (2019) have investigated two different anti-fouling coating applications in terms of fuel consumption. Approximately 20% fuel consumption increase has been recorded at the end of the 9.5 months in the first sea operations using the regular antifouling paint. Before the second operation, the ship entered the dry docking to polish and repair of ship hull and propeller. The second operation of the ship in which higher quality antifouling paint has been used on the hull and propeller has been monitored for 11.5 months period. The fuel consumption has only raised 5% at the end of the period after dry-docking with small fluctuations. Notti et al. (2019) have utilized a fluoropolymer-based anti-fouling paint with a biocide-free feature on a Mediterranean bottom trawler for fuel consumption reduction. The fluoropolymer-based anti-fouling coating has provided fuel consumption saving and carbon emissions. Hull fouling effects have been examined under two different operation modes trawling and cruising throughout approximately three years. Traditional antifouling paint has been applied and measurements regarding Vessel speed and fuel consumption have been recorded for one year before the ship hull has been cleaned. After that fluoropolymer-based anti-fouling paint have been applied over the following two years on trawler ships to compare antifouling systems. A fluoropolymer-based anti-fouling paint has provided almost 10% and 3% fuel savings in Trawling and Cruising operations, respectively compared to the ordinary anti-fouling system.

Farkas et al. (2020) have created different Fouling Conditions in which the roughness length scale is calculated by the height of the largest barnacles and the percentage of the surface covered with barnacles. Container ships, Very Large Crude-oil Carriers, and Bulk carriers equipped with KP505, KP458, and WB propellers, respectively, have been utilized to assess different fouling conditions. The results have revealed that the total resistance coefficients have increased even more than 100% according to the ship type in the most severe pollution conditions. In addition, at least a 50% change in the total resistance coefficients has been observed even at the lowest fouling condition. Erol et al. (2020) have investigated the fouling impact on ship performance deterioration by continuous monitoring. speed loss of around 6% has been recorded on the ferry at the end of the nine months. Laurie et al. (2021) have analyzed performance deterioration due to hull fouling combined with machine learning techniques and data logging systems. Ship hull and propeller fouling have caused a 5.2% change in power requirement in one year.

The ship maintenance intervals must be optimized to avoid the fouling impact most effectively (Farkas et al., 2020). The utilization of effective anti-fouling paint postpones the dry-docking of the ship which not only reduces maintenance costs but also extends the duration of ship operation (Notti et al., 2019) and vice versa (Davidson et al., 2016). Effective anti-fouling systems have also enabled faster ship operations with constant power or meet needed service speed with low power (Turan et al., 2016) that provides a reduction of greenhouse gas emissions and economic efficiency throughout the ship operations (Davidson et al., 2016; Hakim et al., 2017). Apart from fouling, shipload conditions, weather, waves, engine degradation, and aging have also affected fuel consumption rates (Hakim et al., 2017).

Research Gap and Contribution

The literature review indicates the effect of various fouling conditions (Hakim et al., 2019; Notti et al., 2019; Farkas et al., 2020), anti-fouling usage, and various anti-fouling techniques on ship resistance, and fuel saving (Turan et al., 2016; Erol et al., 2020; Laurie et al., 2021). This study aims to fill a research gap by investigating the impact of different fouling conditions on compliance with EEXI and CII requirements. The main motivation is to demonstrate the importance of the fouling effect and possible undesirable efficiency decreases which result in increased carbon tax rates due to low CII ratings or not meeting the EEXI required value. To achieve the objective, a container vessel and its sample route have been determined as the case study. Different anti-fouling techniques that result in various ship resistance increases have been assessed and the impact of the efficiency decreases on EEXI and CII ratings have been depicted and discussed. This research paper can contribute to the literature by demonstrating the importance of the fouling effect from a different perspective and can be useful for academics and maritime sector workers in the related field.

Material and Methods

Methodology

The methodology section has been divided into two sections which are system description and modeling. In the system description subsection, the specifications of the ship and its route have been indicated. The modeling section depicts the mathematical background and assumptions of the calculations. Figure 1 illustrates the flow chart of the methodology used in the paper.

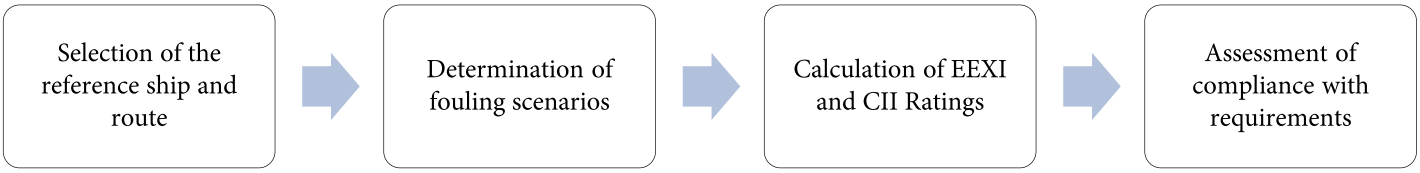


Figure 1. Flowchart of the methodology

Figure 2. The route of the selected container ship (CMA CGM, 2023)

Table 1. Specifications of the reference container vessel

Parameters	**Value**	**Unit**
Gross tonnage	27,910	t
Summer DWT	39,479	t
Length × Beam × Draught	222 × 30 × 11	m^3
Service speed & Max. speed	22 & 24	KN
Capacity	2.824	TEU
Main engine	25,228	kW
Specific fuel oil consumption	174	g/kWh

System Description

Since the biggest percentage of CO_2 emissions in the world fleet came from container ships (European Commission, 2023), a container ship has been selected as a reference vessel for analysis to reveal the effect of ship hull and propeller fouling on EEXI, CII, and CII ratings. The route of the reference container vessel is a liner shipping line and shown in Figure 2. The illustrated route is the real course followed by the reference vessel during its service time.

There are eleven ports of call in the eastbound and westbound routes which are completed in 28 days. The total line length is approximately 6000 nautical miles. The specifications of the container ship have been listed in Table 1.

Modeling

The EEXI Concept formula described in Equation 1 has been used for the calculation (ClassNK, 2021).

$$EEXI\ \left[\frac{g}{ton*mile}\right] = \frac{CO_2\ Conversion\ factor*SFC\left[\frac{g}{kW}*h\right]*Engine\ Power[kW]}{Capacity\ [ton]*V_{ref}} \qquad (1)$$

where *SFC* is specific fuel consumption, *capacity* is the deadweight (DWT) of the ship and V_{ref} is the reference speed of the vessel. Required *EEXI* which is the upper allowable limit for the vessel, can be calculated using Equation 2.

$$Required\ EEXI = \left(1 - \frac{X}{100}\right) * EEXI\ Reference\ Line \qquad (2)$$

The reference value of EEXI calculated in 2023 will have been decreased linearly by applying the reduction factor (X) in the following years. By 2030, there will have been a 20% reduction for the selected vessel in total compared to the initial value (ClassNK, 2021). The reference line of EEXI will have lowered at a specific rate each year according to ship types to provide ongoing advancement in maritime transportation. The calculation of the reference EEDI line for a container ship can be conducted by employing Equation 3.

$$EEDI\ Reference\ Line\ = DWT^{-0.201} x\ 174.22 \qquad (3)$$

Attained CII is calculated by employing Equation 4 based on fuel oil type, carbon factor, the capacity of the ship, and total distance (ClassNK, 2021).

$$Attained\ CII\ = \frac{FC_j * C_{f_j}}{Capacity * D_t} \qquad (4)$$

In Equation 4 the subscript j is the fuel type, FC represents fuel consumption in g, D_t stands for the traveled distance in nautical miles, and C_f is the carbon factor of the fuel. CII will have also been lowered reference value the following year as in EEXI. Unless any improvement is performed on the ship to lower the attained CII value, the CII rating will decrease to lower levels each following year (IMO, 2021a). Required CII is computed by utilizing Equation 5.

$$Required\ CII\ = \left(1 - \frac{Z}{100}\right) * CII_{Ref} \qquad (5)$$

Z refers to the reduction factor relative to the 2019 CII Reference value (CII_{Ref}). The reduction value Z is increasing as 5, 7, 9, and 11 every year throughout 2023-2026 (IMO, 2021a). The increasing rate of reduction every year triggered a decrease in the CII rating. CII_{Ref} is calculated using Equation 6 based on the dimensionless coefficients and Capacity shown in Table 2 for a container ship (IMO, 2021b).

$$CII_{Ref}\ = aCapacity^{-c} \qquad (6)$$

Table 2. Parameters to calculate the reference CII and to decide the CII rating boundaries

Capacity	a	c	d1	d2	d3	d4
DWT	1984	0.489	0.83	0.94	1.07	1.19

Using the values (d1 to d4) CII rating boundaries can be decided for a container vessel. The CII rating scale is illustrated in Figure 3. The negative effect of the hull fouling on the ship resistance power curves directly affects the attained Energy Efficiency Existing Ship Index (EEXI), Carbon Intensity Indicator (CII), and CII rating. EEXI has become mandatory as of January 1, 2023, to reduce greenhouse gas emissions (DNV, 2023). The significant increase in fuel consumption due to hull fouling is a difficult obstacle to meeting both EEXI and CII reference values. Biofouling Management is one of the methods recommended by IMO to comply with CII reference values since the amount of fuel consumption is the most critical parameter in both EEXI and CII calculations (ClassNK, 2021).

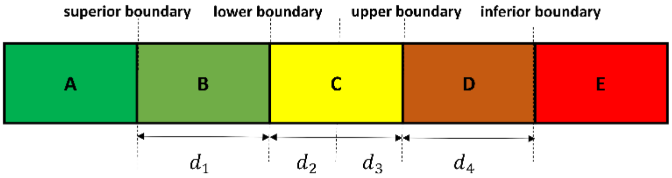


Figure 3. Rating limits according to dd vectors (IMO, 2021c)

The performance of the ships has varied according to the efficiency of the anti-fouling systems used on the ship hull and propeller. In this study, 3 different anti-fouling systems which are low, medium, and high effective have been applied on container ships Hull, and propeller fouling factors that increase the fuel consumption by 5%, 10%, and 20% to maintain the service speed of a container ship have been considered regarding the results of the literature research. EXXI, CII, and CII rating changes over two years have been analyzed based on 3 different performance changes due to fouling. The following assumptions have been performed during the calculations.

- An average speed of 14.4 knots has been acquired when the main engine has been operated at approximately 40% load.
- Auxiliary engines have used MDO up to 10% of the total fuel consumption of the main engine.
- Any application has not been performed to prevent ship hull and propeller fouling for the following two years after anti-fouling applications were performed on the containership.

Results and Discussion

Calculated EEXI and CII values of the reference container ship have been described for 2023 and depicted in Table 3. The reference value of EEXI calculated in 2023 will have decreased linearly in the following years. There will have been a 20% reduction in total compared to the initial value.

Table 3. EEXI and CII values of container ship

Reference EEXI	Attained EEXI	CII_{Ref}	Attained CII
20.76	19.53	11.22	10.61

The change in the Reference Value of EEXI for the reference container ship has been illustrated in Figure 4. Any performance degradations such as hull and propeller fouling and any improvements performed on container ships have not been considered for the calculation of values shown in the figure.

EEXI reference values of the vessel will have met international regulations until the end of 2025 in the base scenario. EEXI values have been calculated considering different anti-fouling applications for the following two years in Table 4.

Table 4. EEXI Values under different anti-fouling systems

Conditions	EEXI Values	
	2024	2025
High effective anti-fouling system (I)	20.02	20.52
Medium effective anti-fouling system (II)	20.5	21.53
Low-effective anti-fouling system (III)	21.48	23.63

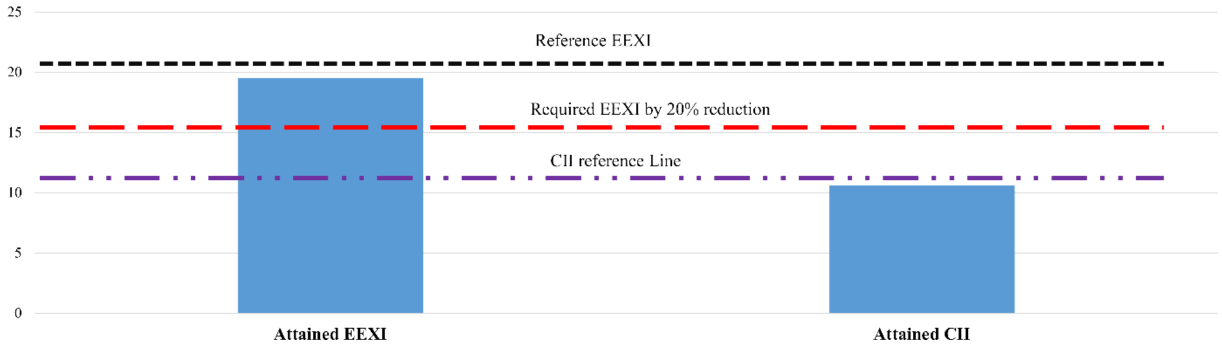


Figure 4. Required and attained EEXI values of the reference container vessel

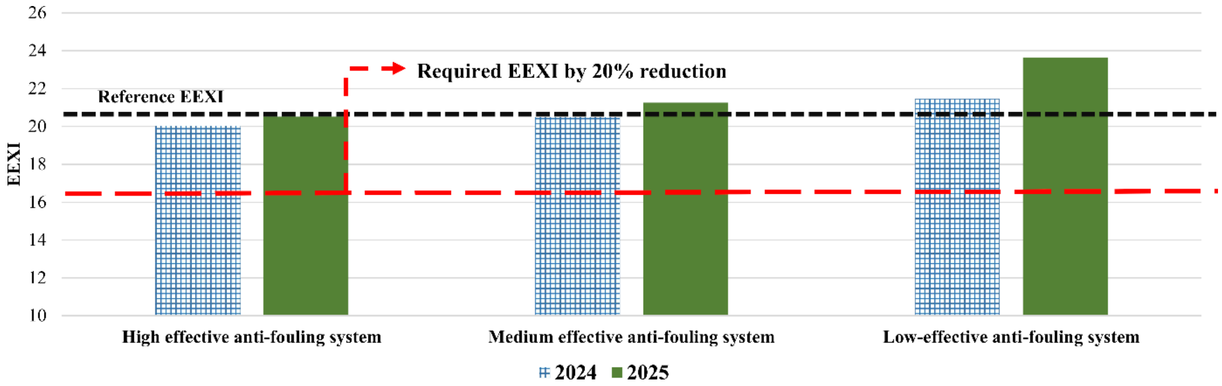


Figure 5. States of meeting EEXI reference values under different anti-fouling applications for container ship

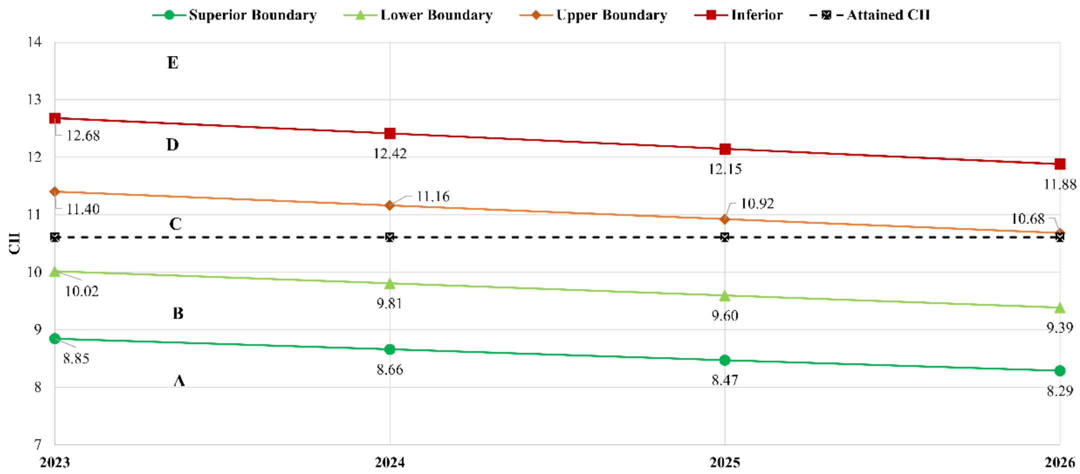


Figure 6. CII boundary limits and attained CII of the reference vessel

Performance decrease and increased fuel consumption due to fouling formation have affected the EEXI values of the reference vessel. Figure 5 indicates whether different fouling applications meet international regulations according to the required EEXI values specified in Table 3.

Superior, lower, upper, and inferior boundaries' values have been calculated for future years by using the coefficients shown in Table 2 for the following years. The boundary limits utilized in CII rating determination have been expressed in Figure 6.

CII ratings of container ships have been calculated by ignoring the hull and propeller fouling effect on the container ship. Different anti-fouling applications' effects on the CII ratings have been described in Table 5.

Table 5. CII ratings under different anti-fouling applications for the reference ship

Condition	**I**		**II**		**III**	
Year	2024	2025	2024	2025	2024	2025
Attained CII	10.87	11.15	11.14	11.70	11.67	12.84
Rating	C	D	C	D	D	E

Energy efficiency measures have been taken to provide sustainable maritime transportation by maritime authorities. An effective anti-fouling system which is one of the energy-saving methods both protects the hull of the ship and prevents performance degradation. after the ship is left from dry docking in which the ship's hull and propeller are cleaned, operational performance is at the highest level. The effective anti-fouling system minimally affects the ship's performance and provides the ship to sustain the highest level of performance. This helps ships to pass the EEXI and CII thresholds that became mandatory after 1st January 2023. EEXI, CII, and CII ratings have been calculated by utilizing logging performance data getting from ships. Therefore, the high-effective anti-fouling system has minimized ship performance fluctuations throughout two dry docking periods.

The EEXI value of the selected container ship has met international regulations by staying below the EEXI reference value on the determined route when the bio-fueling effect on the ship's hull and propeller has been ignored. After the end of 2023, the effect of fouling on the EEXI value of the container ship has been examined by utilizing 3 different anti-fouling systems. While the container ship equipped with the high-effective anti-fouling system has met the EEXI reference value, the required EEXI of 20% reduction will not be met by the high-effective anti-fouling system. On the other hand, the EEXI reference value will have been met until the end of 2024 by the medium effective anti-fouling system. However, the EEXI reference value will not have been met when the year 2026. In addition, the EEXI reference value has not been met by a low-effective anti-fouling system at any time. Attained CII of the container ship has met international regulations by the end of 2023 staying under the CII ref value when the bio-fouling effect is ignored. Moreover, the Container ship has been C level under the CII rating considering throughout the boundaries condition 2019 to 2026. However, the CII rating of the container ship is C for 2024 and D for 2025 in high and medium effective anti-fouling system applications when the bio-fueling is considered on the ship's performance. it is D for 2024 and E for 2025 in low-effective anti-fouling system applications.

Therefore, new applications should have been performed to meet the EEXI reference value and CII_{Ref} following years besides an effective fouling system. The utilization of alternative or renewable fuels such as LNG, methanol, ammonia, biofuels, hydrogen, nuclear, solar, wind, and wave power has come to the fore in complying with the EEXI and meeting CII_{Ref} in maritime transportation. Moreover, the utilization of Shaft power limitation (SHaPoLi) and engine power limitation (EPL) on ship propulsion systems have provided advantages meeting EEXI and CII reference values. When all these applications have been used in combination on the ship, they will also ensure that CII ratings are maintained at A level for a long time.

Conclusion

A significant part of international transport has been carried out by maritime transportation. Therefore, the operational efficiency of ships in maritime transport has a global impact, both environmentally and economically. the operational efficiency of the ships has deteriorated by many factors such as the ship's crew experience, weather conditions, sea state, and more. Biofouling is one of the factors that reduce the ship's performance in terms of both fuel consumption and power. Increased fuel consumption and added power needed due to biofouling is a major obstacle to achieving EEXI, and CII reference values getting even lower over the years. The performance of the ships has been maintained at a high level for a long time with the high-efficient anti-fouling systems after launching from the dry dock in which the ship's hull and propeller are cleaned. However, the ship's performance-enhancing applications should be performed as well as maintaining the existing performance to comply with the new regulations. The utilization of alternative and renewable fuels, SHAPoLi, and EPL applications have stood out within the scope of energy efficiency measures.

This study will help reveal the anti-fouling systems' impact on EEXI, CII, and CII ratings that can be beneficial for academicians, marine engineers, and ship surveys whose working fields are related to the fouling-related fuel consumption increments. Future studies can cover the analysis based on recorded speed and fuel consumption data to observe the impact of the biofouling growth, the effect of the antifouling techniques on the EEXI, CII, and CII ratings, or an experimental study to observe the biofouling effect and timing on the hull or propeller surface.

Compliance With Ethical Standards

Authors' Contributions

MB: Conceptualization, Investigation, Formal analysis, Methodology, Writing.
OY: Conceptualization, Investigation, Visualization, Methodology, Writing.
Both authors read and approved the final manuscript.

Conflict of Interest

The authors declare that there is no conflict of interest.

Ethical Approval

For this type of study, formal consent is not required.

Data Availability Statements

All data generated or analyzed during this study are included in this published article.

References

Bayraktar, M., & Yüksel, O. (2023). Analysis of the nuclear energy systems as an alternative propulsion system option on commercial marine vessels by utilizing the SWOT-AHP method. *Nuclear Engineering and Design*, *407*, 112265. https://doi.org/10.1016/j.nucengdes.2023.112265

ClassNK. (2021). Outlines of EEXI regulation. Retrieved on March 2, 2023, from https://www.classnk.or.jp/hp/pdf/activities/statutory/eexi/eexi_rev3e.pdf

CMA CGM. (2023). SSLMED Cross Med Service. Retrieved on March 5, 2023, from https://www.cma-cgm.com/products-services/line-services/flyer/CROSSMED

Davidson, I., Scianni, C., Hewitt, C., Everett, R., Holm, E., Tamburri, M., & Ruiz, G. (2016). Mini-review: Assessing the drivers of ship biofouling management–aligning industry and biosecurity goals. *Biofouling*, *32*(4), 411-428. https://doi.org/10.1080/08927014.2016.1149572

DNV. (2022). Cybutryne banned in anti-fouling systems from 1 January 2023. Retrieved on February 11, 2023, from https://www.dnv.com/news/cybutryne-banned-in-anti-fouling-systems-from-1-january-2023-224593

DNV. (2023). EEXI – Energy Efficiency Existing Ship Index. Retrieved on March 17, 2023, from https://www.dnv.com/maritime/insights/topics/eexi/index.html

Erol, E., Cansoy, C. E., & Aybar, O. Ö. (2020). Assessment of the impact of fouling on vessel energy efficiency by analyzing ship automation data. *Applied Ocean Research*, *105*, 102418. https://doi.org/10.1016/j.apor.2020.102418

European Commission. (2023). Fourth annual report from the European Commission on CO_2 emissions from maritime transport (period 2018-2021). Retrieved on March 15, 2023, from https://climate.ec.europa.eu/system/files/2023-03/swd_2023_54_en.pdf

Farkas, A., Degiuli, N., Martić, I., & Dejhalla, R. (2020). Impact of hard fouling on the ship performance of different ship forms. *Journal of Marine Science and Engineering*, *8*(10), 748. https://doi.org/10.3390/jmse8100748

Hakim, M. L., Nugroho, B., Nurrohman, M. N., Suastika, I. K., & Utama, I. K. A. P. (2019). Investigation of fuel consumption on an operating ship due to biofouling growth and quality of anti-fouling coating. *IOP Conference Series: Earth and Environmental Science*, *339*(1), 012037.

Hakim, M. L., Utama, I. K. A. P., Nugroho, B., Yusim, A. K., Baithal, M. S., & Suastika, I. K. (2017). Review of correlation between marine fouling and fuel consumption on a ship. *Proceeding of SENTA: 17th Conference on Marine Technology*, Greece. pp. 122-129.

IEA. (2009). *Transport, Energy and CO_2 Moving towards Sustainability*. Retrieved on March 1, 2023, from https://www.iea.org/reports/transport-energy-and-co2

IMO. (2003). Anti-fouling systems. Retrieved on March 21, 2023, from https://wwwcdn.imo.org/localresources/en/OurWork/Environment/Documents/FOULING2003.pdf

IMO. (2012). Guidance for minimizing the transfer of invasive aquatic species as biofouling (Hull Fouling) for Recreational Craft. Retrieved on March 21, 2023, from https://wwwcdn.imo.org/localresources/en/OurWork/Environment/Documents/MEPC.1-Circ.792.pdf

IMO. (2021a). Guidelines on the operational carbon intensity reduction factors relative to reference lines (CII reduction factors guidelines, G3). Retrieved on January 21, 2023, from https://wwwcdn.imo.org/localresources/en/OurWork/Environment/Documents/Air%20pollution/MEPC.338(76).pdf

IMO. (2021b). 2021 Guidelines on the reference liens for use with carbon intensity indicators (CII Reference Llnes rating guidelines, G2). Retrieved on January 12, 2023, from https://wwwcdn.imo.org/localresources/en/OurWork/Environment/Documents/Air%20pollution/MEPC.337(76).pdf

IMO. (2021c). 2021 Guidelines on the operational carbon intensity rating of ships (CII rating guidelines, G4). Retrieved on January 1, 2023, from https://wwwcdn.imo.org/localresources/en/OurWork/Environment/Documents/Air%20pollution/MEPC.339(76).pdf

IMO. (2023a). IMO and Sustainable Development. Retrieved on March 15, 2023, from: https://wwwcdn.imo.org/localresources/en/MediaCentre/HotTopics/Documents/IMO%20SDG%20Brochure.pdf

IMO. (2023b). Biofouling. Retrieved on January 21, 2023, from https://www.imo.org/en/OurWork/Environment/Pages/Biofouling.aspx

IMO. (2023c). EEXI and CII - ship carbon intensity and rating system. Retrieved on March 17, 2023, from https://www.imo.org/en/MediaCentre/HotTopics/Pages/EEXI-CII-FAQ.aspx

Konur, O., Yuksel, O., Korkmaz, S. A., Colpan, C. O., Saatcioglu, O. Y., & Koseoglu, B. (2023). Operation-dependent exergetic sustainability assessment and environmental analysis on a large tanker ship utilizing Organic Rankine cycle system. *Energy*, *262*, 125477. https://doi.org/10.1016/j.energy.2022.125477

Laurie, A., Anderlini, E., Dietz, J., & Thomas, G. (2021). Machine learning for shaft power prediction and analysis of fouling related performance deterioration. *Ocean Engineering*, *234*, 108886. https://doi.org/10.1016/j.oceaneng.2021.108886

Levin, S. A. (2013). *Encyclopedia of Biodiversity* (2nd ed.). Elsevier Science.

Munk, T., Kane, D., & Yebra, D. M. (2009). The effects of corrosion and fouling on the performance of ocean-going vessels: A naval architectural perspective (pp. 148-176). In Hellio, C., & Yebra, D. (Eds.), *Advances in marine antifouling coatings and technologies*. Woodhead Publishing.

Notti, E., Figari, M., Sala, A., & Martelli, M. (2019). Experimental assessment of the fouling control coating effect on the fuel consumption rate. *Ocean Engineering*, *188*, 106233. https://doi.org/10.1016/j.oceaneng.2019.106233

Turan, O., Demirel, Y. K., Day, S., & Tezdogan, T. (2016). Experimental determination of added hydrodynamic resistance caused by marine biofouling on ships. *Transportation Research Procedia*, *14*, 1649-1658. https://doi.org/10.1016/j.trpro.2016.05.130

UNCTAD. (2023). Climate change adaptation and maritime transport. Retrieved on March 25, 2023, from https://unctad.org/topic/transport-and-trade-logistics/policy-and-legislation/climate-change-and-maritime-transport

United Nations. (2023). Goal 13: Take urgent action to combat climate change and its impacts. Retrieved on March 7, 2023, from https://www.un.org/sustainabledevelopment/climate-change/

Wartsila. (2023). Anti-fouling paint. Retrieved on January 2, 2023, from https://www.wartsila.com/encyclopedia/term/anti-fouling-paint