Environmental Research 222 (2023) 115348

Contents lists available at ScienceDirect

Environmental Research

journal homepage: www.elsevier.com/locate/envres

Implementation of the energy efficiency existing ship index and carbon intensity indicator on domestic ship for marine environmental protection

Lai Fatt Chuah [a,**], Kasypi Mokhtar [a], Siti Marsila Mhd Ruslan [a], Anuar Abu Bakar [b], Mohd Azhafiz Abdullah [a], Nor Hasni Osman [c], Awais Bokhari [d,e], Muhammad Mubashir [f], Pau Loke Show [g,h,i,j,*]

[a] Faculty of Maritime Studies, Universiti Malaysia Terengganu, Terengganu, Malaysia
[b] Faculty of Ocean Engineering Technology and Informatics, Universiti Malaysia Terengganu, Malaysia
[c] School of Technology Management and Logistics, Universiti Utara Malaysia, 06010, Sintok, Kedah Darul Aman, Malaysia
[d] Department of Chemical Engineering, COMSATS University Islamabad (CUI), Lahore Campus, Lahore, Punjab, 54000, Pakistan
[e] Sustainable Process Integration Laboratory, SPIL, NETME Centre, Faculty of Mechanical Engineering, Brno University of Technology, VUT Brno, Technická 2896/2, 616 00, Brno, Czech Republic
[f] Department of Petroleum Engineering, School of Engineering, Asia Pacific University of Technology and Innovation, 57000 Kuala Lumpur, Malaysia
[g] Zhejiang Provincial Key Laboratory for Subtropical Water Environment and Marine Biological Resources Protection, Wenzhou University, Wenzhou 325035, China
[h] Department of Chemical Engineering, Khalifa University, Shakhbout Bin Sultan St - Zone 1, Abu Dhabi, United Arab Emirates
[i] Department of Sustainable Engineering, Saveetha School of Engineering, SIMATS, Chennai 602105, India
[j] Department of Chemical and Environmental Engineering, Faculty of Science and Engineering, University of Nottingham Malaysia, 43500 Semenyih, Selangor, Malaysia

ARTICLE INFO

Keywords:
Decarbonization
Shipping
Cost-effectiveness
Malaysian-registered domestic ships

ABSTRACT

The International Maritime Organization has set a goal to achieve a 50% reduction of total annual greenhouse gas emission related to the international shipping by 2050 compared to the 2008 baseline emissions. Malaysia government has taken an initiative to investigate the assessment (cost-effectiveness) of this International Maritime Organization's short-term measure on Malaysian-registered domestic ships although this measure is only for international merchant ship. To achieve this, this paper collected the ship's data from the shipowners from 25 sample ships. Engine power limitation is the most cost-effective option, but low power limits can lead to substantially increased sailing times. Based on cost-efficiency analysis, it creates for the purpose of compliance with the operational carbon intensity indicator. It found that even if it is possible to bring an asset back into service, it may not be possible to do so in a manner that generates a profit or complies with applicable regulations. In these situations, it may be more prudent to scrap the asset rather than run the risk of having it become a stranded asset. This is especially true for older tankers. Alternatives with lengthy payback periods are not desirable for the domestic tanker fleet that is already in operation.

1. Introduction

When compared to other forms of commercial transportation, marine shipping is the method that is the safest (Chuah et al., 2022a), most cost-effective (Cheah et al., 2016), most energy-efficient (Bokhari et al., 2016), and least harmful to the environment (Chuah et al., 2021a). The worldwide shipping industry is responsible for more than 90% of all commercial activity (Chuah et al., 2022b) and is the sixth greatest emitter among nations (2.89%) in terms of greenhouse gas (GHG) emissions (Chuah et al., 2015). It is clear that marine trade has continued to expand all over the world over the past several decades (Bokhari et al., 2020), outpacing the expansion of other industries (Malik et al., 2019) and bringing with it the unintended consequence of an increase in GHG emissions (Asif et al., 2019), which is a threat to the environment (Chuah et al., 2022c).

There are 1.6×10^6 seafarers working on a fleet of 92,647 commercial ships delivering all kinds of goods throughout the globe (4,362,737 port visits and 11×10^9 t of seaborne trade (Chuah et al., 2022d). About 43% (474 ships type specific) of the total Malaysian-registered ship (1115 ships type specific) was 400 GT and

* Corresponding author. Department of Chemical Engineering, Khalifa University, Shakhbout Bin Sultan St - Zone 1, Abu Dhabi, United Arab Emirates.
** Corresponding author.
E-mail addresses: lfchuah@umt.edu.my (L.F. Chuah), pauloke.show@nottingham.edu.my, pauloke.show@ku.ac.ae (P.L. Show).

https://doi.org/10.1016/j.envres.2023.115348
Received 23 November 2022; Received in revised form 1 January 2023; Accepted 21 January 2023
Available online 30 January 2023

more voyage in domestic and international waters (Chuah et al., 2021b). General cargo (45%) was the top followed by tanker ship (32%), passenger/vehicle RoRo ship (14%), container ship (6%) and bulk carrier (3%) (Table 1). These two top types of ship have almost half of the domestic ships in Malaysia. Ships continued to carry essential goods and medical supplies even at the midst of the COVID-19 pandemic, and ports stayed open to facilitate distribution.

In 2018, the International Maritime Organization (IMO) set out to achieve two key targets in order to increase shipping's decarbonization. In the first place, by 2030 and 2050, a decrease in carbon dioxide emissions per tonne-mile of freight of 40% and 70%, is the goal (Mukhtar et al., 2020; Tawfik et al., 2021; Nawaz et al., 2022). Second, to work towards a reduction of 50% of the total annual greenhouse gas emissions by the year 2050, while simultaneously attempting to completely phase them out in accordance with the Paris Agreement to keep the rise in global temperature well below 1.5 °C-2.0 °C. Both are going to be measured in comparison to the emissions that were related in 2008 (Bokhari et al., 2014; Yusup et al., 2015).

There will be three phases of further action measures based on the normative requirements that are mandated by the IMO viz. the short-term (technical and operational measures: 2018–2023), mid-term (Market based Measures-MBMs: 2023–2030) and long-term (alternative fuel: beyond 2030). The short-term measure was agreed upon during the MEPC76 meeting of the Marine Environmental Protection Committee in the year 2021. The technical criteria that were previously only applicable to ships that were newly built (400 GT and above) through the Energy Efficiency Design Index (EEDI) are now expanded to encompass existing ships (400 GT and above) through the Energy Efficiency Existing Ship Index (EEXI). In an effort to reduce GHG from existing ships, two significant interventions were implemented. A one-time activity is required to meet the EEXI criteria, which must be completed by 2023. The EEXI standards include reduction requirements with relation to the EEDI reference line, which must be followed by ships of varying capacities. MEPC 76 mandates that engine manufacturers consult in order to get the achieved and needed EEXI based on engine parameters. Retrofits of energy efficiency technology (EET) may be necessary for these ships if shaft/engine power limitation (SHaPoLi/EPL) is not sufficient to fulfil the requirement, such as retrofitting a bulbous bow optimized for the actual operational profile, air lubrication systems (ALS), optimized propeller, wind-assisted propulsion systems (WAPS), propulsion improving devices (PIDs) viz. twisted rudders, rudder bulbs in combination with propeller caps, propeller boss cap fins (PBCF), vortex generator fins (VGF), pre-swirl stators (PSS), pre-swirl ducts (PSD), stern ducts and wake equalizing ducts (WED).

The paper is organized as follow. Section 2 provides a literature review on the previous studies related to the analysis of carbon dioxide reduction potentials. In Section 3, materials and methos are described to develop the study design and data collection. In Section 4, operational data (Jan 1, 2021–Dec 31, 2021) from 19 tanker ships and 5 container ships as part of a sample to give the evidence-based viewpoint were thoroughly analyzed. Finally, the conclusion and suggestions for further research are presented in Section 5.

2. Literature review

The Ship Energy Efficiency Management Plan (SEEMP) has been required for all ships with a gross tonnage of 400 GT or more. This includes both new and existing ships, with the exception of those that are not propelled by mechanical means, as well as platforms such as floating production storage and offloading (FPSO), Floating storage unit (FSU) and drilling rig, regardless of its mode of propulsion. In line with MARPOL Annex VI, all ships with 400 GT or more that are engaged in international voyage are required to carry a copy of Part I of the SEEMP on board. This requirement goes into effect on or after January 1, 2013. The amendments to MARPOL Annex VI that were adopted in 2016 require ships with 5000 GT or more that are engaged in an international voyage to collect and report their fuel oil consumption data to the administration or a recognized organization (RO) beginning in the year 2019. Under the IMO data collection system (DCS), ships must design a ship fuel oil consumption data collecting strategy (SEEMP Part II) and have that plan approved by administration or RO. Additional amendments to MARPOL Annex VI (IMO Resolution MEPC.328 (76)) were approved during the 76th session of the IMO's MEPC76, and the carbon Intensity Indicator (CII) rating will be implemented beginning on January 1, 2023. This rating will be based on the amount of fuel that is consumed annually by each ship.

The ships with 5000 GT or more that are subject to the CII rating are required to develop a SEEMP (Part III) that comprises required CII values over the next three years, implementation plan for reaching the required CII, CII calculation methodology and measures for self-evaluation & improvement. This plan should be confirmed by the administration or RO. The CII requirement is dropped by 2% every year beginning in 2023. A grading system based on the fleet's 2019–2021 performance has been implemented to measure the annual performance of ships. CII ratings will be applied to IMO DCS data starting in 2023, and by 2024, each ship will be assigned one of five possible grades, which are A to E. Corrective measures are not applied to ships with a C or above rating. In contrast, D grade for 3 consecutive years or E results in a SEEMP remedial measures.

The study of Schroer et al. (2022) uses a novel evidence-based bottom-up method, and the results reveal that compliance is difficult and costly. Through the use of a simulation model designed for the purpose of estimating the yearly carbon dioxide emissions of a Panamax containership, Guan et al. (2015) investigated the possibility for a cut-out of a turbocharger to reduce emissions of carbon dioxide. Psaraftis et al. (2021) provides an overview and discussion of prospective Market Based Measures (MBMs) under the Initial IMO Strategy for reducing ship GHG emissions. Rutherford et al. (2020) are looking into the engine power restriction (EPL) option, which is one of the most popular recommendations for EEXI compliance. According to marginal abatement cost curves, Irena et al. (2021) investigated the cost-effectiveness of several emission reduction techniques that might be implemented onboard various types of ships. Mallouppas and Yfantis (2021) provide a contribution to the process of evaluating the degree of maturity exhibited by various technical possibilities. Bouman et al.

Table 1
Sampling from the total Malaysian ship registration plying in domestic waters.
Source: Author's own elaboration from compilation database.

Ship type	Traditional registry	≥400 GT	MISR	≥400 GT	Total	Total ≥400 GT	Total ≥400 GT plying domestic
LNG/LPG carrier	32	32	0	0	32	32	0
Oil/chemical tanker	253	134	0	0	253	134	**40**
Product tanker	14	14	0	0	14	14	4
Water tanker	10	2	0	0	10	2	2
Container ship	28	28	0	0	28	28	**8**
General cargo	442	216	0	0	442	216	65
Bulk carrier	12	11	1	1	13	12	4
Passenger/Vehicle RoRo ship	323	36	0	0	323	36	20
Total					1115	474	143

(2017) reviews 150 research to offer a complete overview of carbon dioxide emissions reduction potentials and measures in the literature. It identifies promising areas, such as technology and operating procedures, and quantifies their mitigation potential (Chuah et al., 2017).

The provision of EEXI is solely applied to all ships of 400 GT and above, which plying international voyage, but the administration of party should ensure the ships plying within domestic waters adopts an appropriate measure so far as is reasonable and practical. Malaysia is taking aggressive efforts in contemplating the adoption of the remaining conventions by becoming an elected Council Member of the IMO since 2005. However, the adoption of these conventions is subject to Malaysia's specific conditions and capabilities. In order to accomplish this goal, Malaysia has assigned two maritime attachés to work at the IMO on a full-time basis. Due to this, Malaysia has taken an initiative to assess on cost-effectiveness of IMO's EEXI and CII measures for decarbonizing Malaysian-registered domestic ships. Malaysia encourages shipowners (domestic voyage) to study the cost-effectiveness and practicality of various fuel-saving alternatives. These solutions may have a technical or an operational focus. It is possible to find research that compare or explore a particular compliance option in detail. When looking into particular compliance possibilities, evidence-based research is frequently employed. However, shipowners are obsessed with the effects on low- and middle-income nations and emerging economies. There is very limited scholastic information on the current status of Malaysian-registered domestic ship's energy efficiency performance. No papers have focused on domestic ship's energy efficiency performance. To obtain the input data from the stakeholders, the workshop was conducted on 25 to July 26, 2022, with collaboration of Malaysia Shipowners' Association (MASA), Marine Department Malaysia, Malaysian Transport Ministry and Universiti Malaysia Terengganu.

The following research questions can be used to fill in the remaining gaps in the existing body of literature. First, what are the implications for shipowners/operators of complying with IMO's short-term measures based on real operating data for domestic ships that aren't in compliance? Second, what are the effects of complying with the IMO's short-term measures on different ship sizes, ship types, and ship ages? Third, which compliance methods for existing ships have the most potential to reduce emissions? Which of the compliance alternatives identified for the study ships should be used? A bottom-up strategy is used in this study to answer the problems posed above. The objectives of this paper are examined the influence of short-term measure on the overall cost effectiveness of ships, as well as to determine the potential reductions in carbon dioxide emissions that can be achieved through technical and operational compliance options for individual ships. This paper examines operational data from 19 tanker ships and 5 container ships as part of a sample to give the evidence-based viewpoint. The findings of this data will be used as crucial data information to build effective methods in carbon dioxide reduction, catering to the demands of the Malaysian shipping sector, and assisting policymakers in making decisions in order to further enhance marine environmental protection.

3. Materials and methods

After determining both the broad and narrow aims of this research project, the next step was to construct the research itself in addition to developing a method to collect data. The procedure for carrying out research in this paper is depicted in Fig. 1. Within this paper, this research employs a mixed method of data collection and analysis. Exploration of the work area, which entails an extensive review of important data gleaned from previous investigations and records, is the primary tactic for the collection of information. The shipowner's very own database system constitutes a substantial portion of this investigation. At the beginning of the study, a literature review was conducted before the research problem was identified. By looking at Malaysia's need to access the cost-effectiveness of IMO's EEXI and CII measures for decarbonizing Malaysian-registered domestic ships, two research objectives were developed and further assisted with devising the methodological approach. To obtain the input data from the stakeholders, the workshop was conducted at the Everly, Putrajaya on 25 to July 26, 2022, with collaboration of Malaysia Shipowners' Association (MASA), Marine Department Malaysia, Malaysian Transport Ministry and Universiti Malaysia Terengganu. To evaluate the numerous archive sources, Google Alert was also utilized to locate pertinent material on EEXI. In qualitative research, the concept of interpretation serves as the

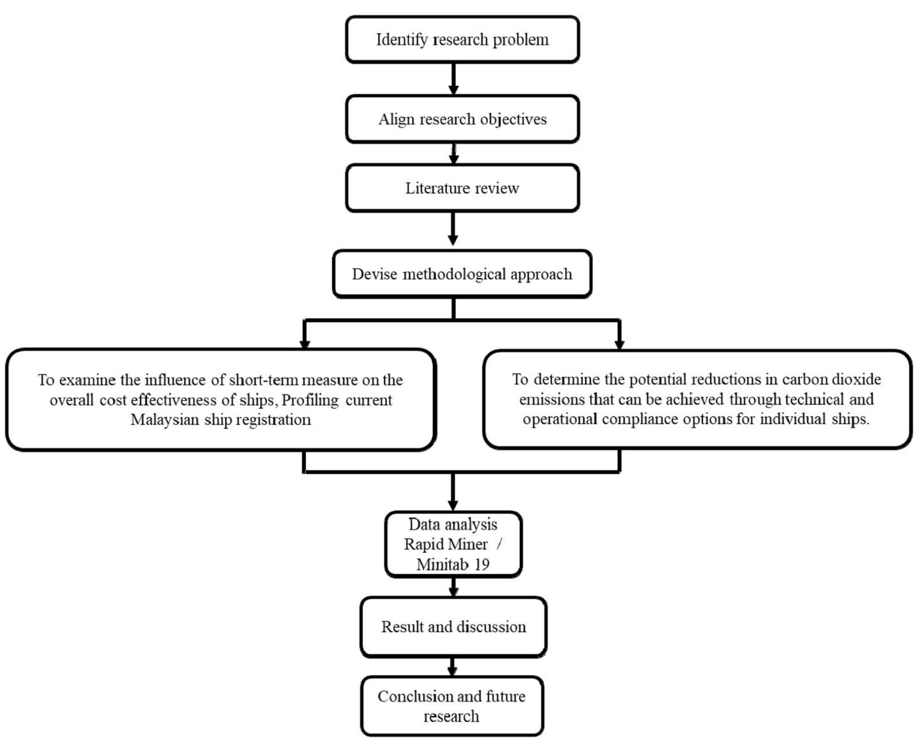

Fig. 1. Methodological approach. Source: Own elaboration.

foundation, as stated by Chuah et al. (2022d). In this context, documents, papers, and studies that were selected as credible sources were picked as a result of the reputation of the website, organization, or institute that published them, as well as the contribution that it made to the maritime industry. The acquired information was analyzed by Rapid Miner and Minitab. As a direct consequence of this, the results of the first and second objectives are presented and investigated in greater depth in Section 4.

4. Results and discussion

The values of attained EEXI, required EEXI and age of 24 sample ships for phase 2 viz. Jan 1, 2020 to Dec 31, 2024, can be seen in Fig. 2. The correlation between EEXI and age of ship for 24 sample ships is shown in Fig. 2. It can be seen that only about 26% (tanker ships- T1, T2, T9-, T14, T15) and 100% (all container ships-C1-C5) of the sample ships are met to the EEXI requirement. Even if the ship's age plays a significant role in establishing the minimum EEXI values that must be met, this does not imply that a similarly high EEXI must also be achievable, as shown in Fig. 2.

The short-term measurements are influenced by age in two independent but indirect ways. Younger ships are predicted to have greater environmental performance because of improved design, which is a result of the EEDI regulations and other factors. Even the age of the ship is a factor in determining the needed EEXI values, it does not necessarily result in a comparable EEXI as represented in Fig. 2 since operational

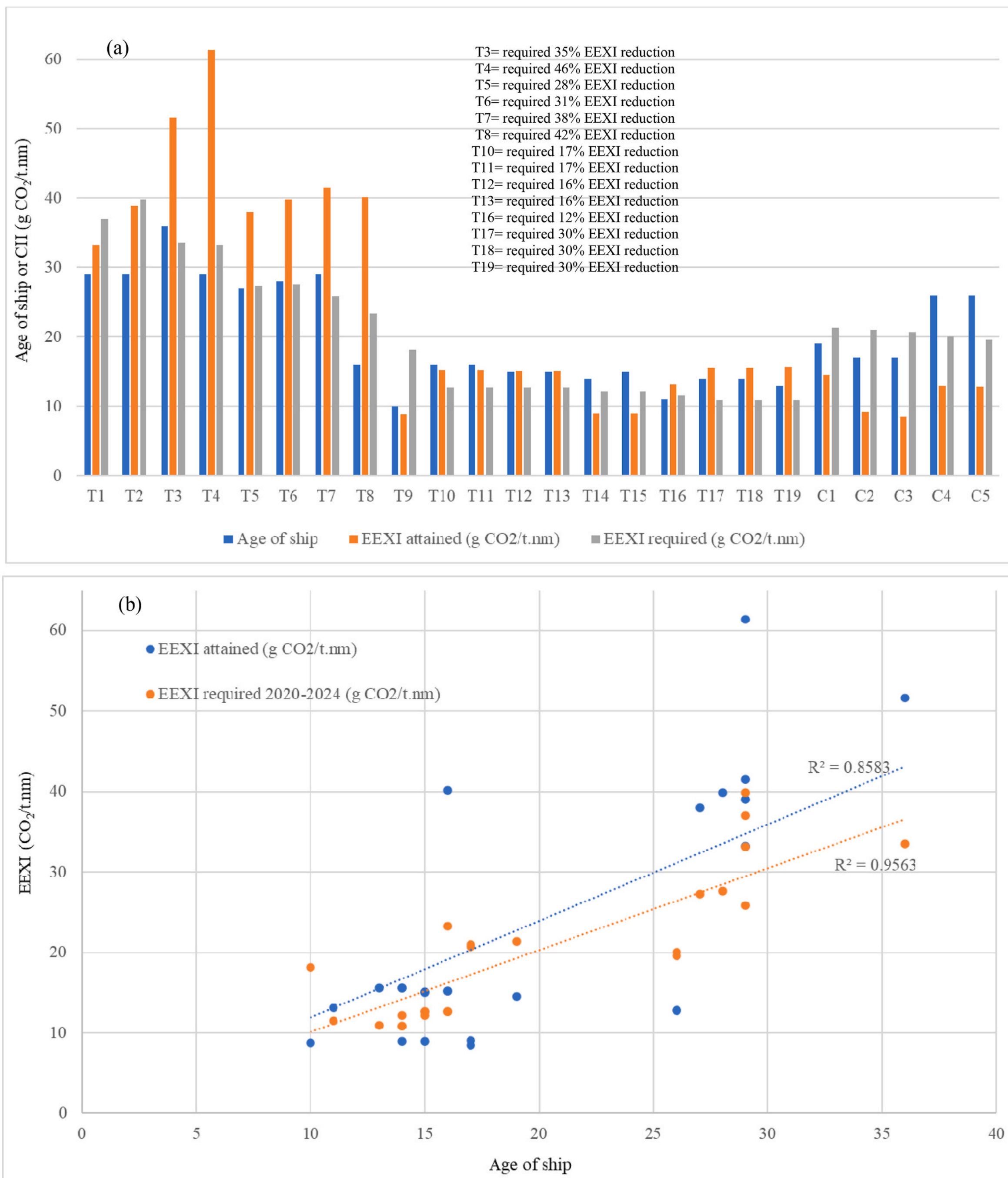

Fig. 2. a) EEXI attained, EEXI required, age and b) the correlation between EEXI and age of ship for phase 2's (Jan 1, 2020 to Dec 31, 2024) 24 sample ships. Source: Author's own elaboration from compilation database.

conditions play a role. Based on the sample ship's results, the other non-compliance domestic sample ships required an EEXI reduction from 12% to 46%.

As can be seen in Fig. 3, the IMO short-term measures include a one-time requirement for EEXI to be satisfied in 2023, as well as yearly reductions in terms of CII for the years 2023–2030. The CII reduction for 2027–2030, as well as the needed remedial actions for non-compliance, and the enforcement mechanism that corresponds to it, will be set by the IMO's 2026 review process. This study makes the assumption that there will be a 2% yearly decrease for 2027 onward. The size of the ship has an effect on the technical indicators. As can be seen in Fig. 3, it is well proven that the operational index, also known as CII, of a ship decreases as the size of the ship increases. Fig. 4 presents the positioning of the sample ships in relation to the attained CII/required CII including its CII rating line at the beginning 2023 and end 2030 for the study period. Additionally, the corresponding improvements that are required are shown in Table 2 for tanker ships and Table 3 for container ships. T15 with the age of 15 years can achieve the label C until 2030 (year of label D for three consecutive years) compared to the other same age of tanker ships viz. T12 and T13 with marginally different deadweight (8%) and gross tonnage (5%). It is possible that this is the outcome of the ship practising just-in-time arrival, which leads to very short periods of time spent at anchor as perceived by the ship. By decreasing the amount of time spent in port and permitting even slower travel speeds, there is the possibility of realising a greater reduction potential.

In 2023, all ships, with the exception of T10, T11, T17, T18, and T19, are able to achieve the minimum required Label C. A required carbon dioxide reduction of the non-compliance tanker domestic ship is range between 17% and 49% to be brought up to the necessary Label C standard. This indicates that necessary steps will be implemented if voluntary remedial efforts are not completed by 2024. The rating of every ship goes down as a result of the ever-increasing stringency of the standards throughout the years. By 2030, all ships except T14, T16 and C1–C5 will rate D or E.

The selection of compliance choices (both operational and technical compliance options) is based on solutions that are now available and ready to be implemented using technology, with the shipowner's perspective being taken into consideration. The operational aspect of the CII regulation inherently suggests that potential remedies involve a drop in speed (EPL). Virtual arrival (VA) is a second operational option which less than 1% reduction potential stated by Schroer et al. (2022), whereas the remaining options are comprised of technological solutions such as variable frequency drive (VFD), waste heat recovery system (WHRS), turbocharger cut-out (TCCO) and auxiliary engine economizer (AEE). Table S1 provides a summary of the reduction potential values and costs based on previous research.

The following question that has to be solved is which option combination should be implemented in order to fulfil these prerequisites. This predicament is analogous to the well-known "knapsack issue." An extra choice is provided so that users may take advantage of the synergistic advantages that result from coupling a WHRS with the appropriate VFD application. By default, EPL restrictions that are lower than 50% MCR are connected to a TCCO installation. It is important to keep in mind that the installation of an EPL might potentially have an effect, either directly or indirectly, on the reduction potentials of other compliance solutions (WHRS and VFD) that are being investigated in

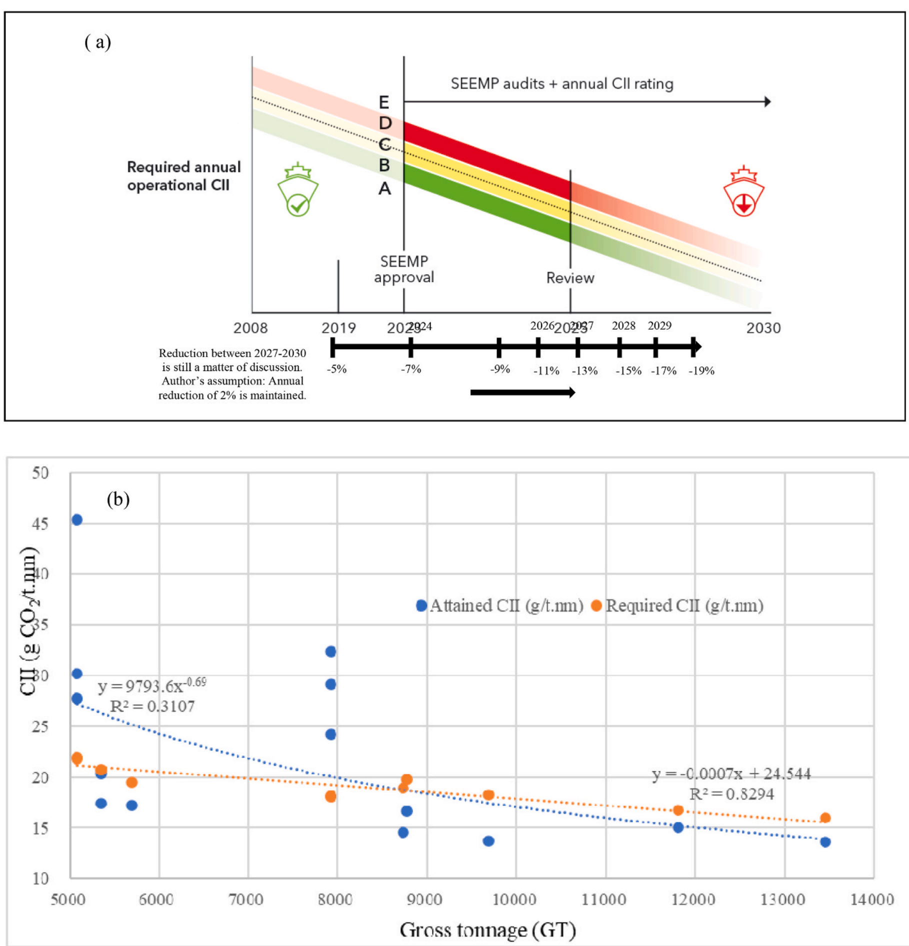

Fig. 3. a) CII rating of ship type specific and b) relation between CII and gross tonnage for 15 sample ships Source: Author's own elaboration from compilation database.

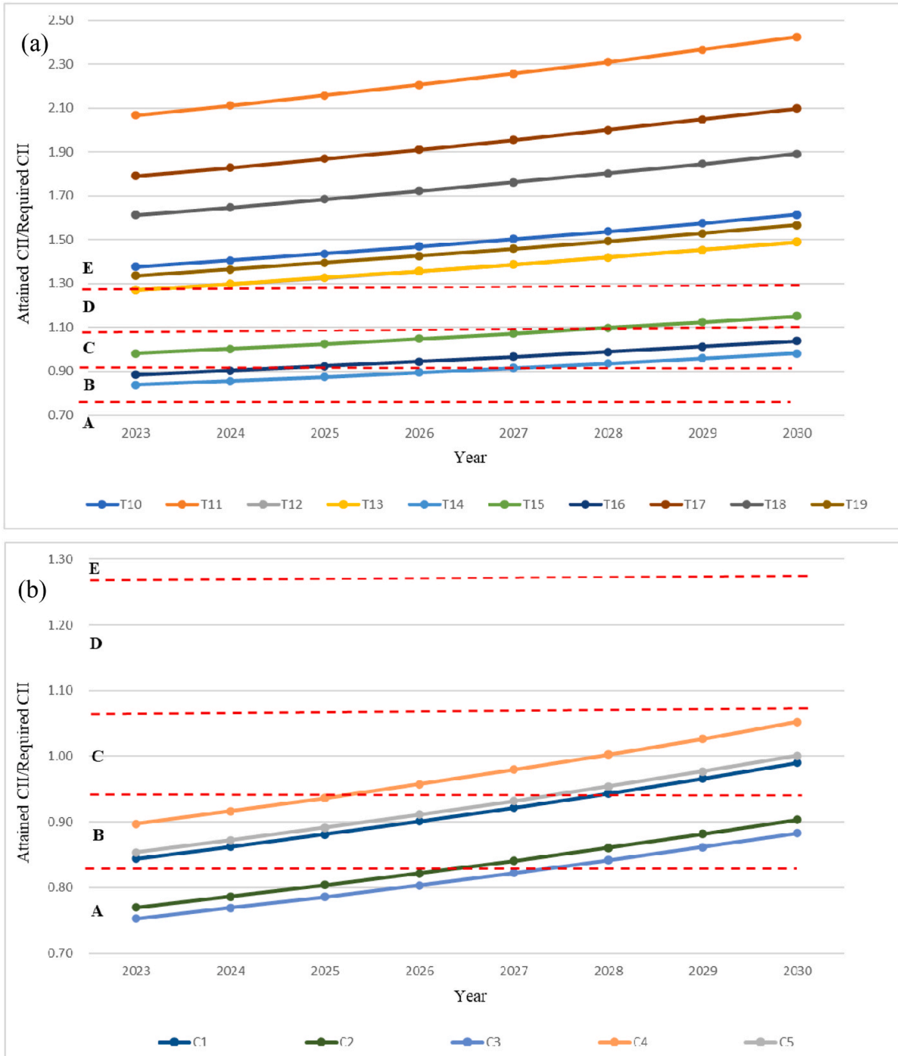

Fig. 4. CII rating (a) 10 sample tanker ships and (b) 5 sample container ships depending on CII value for 2023 to 2030. Source: Author's own elaboration from compilation database.

this study. No other dependencies have been taken into account save a separate study of a WHRS and VFD combo and an evaluation of WHRS's reduction potential that is reliant on ME power. In addition, the TCCO does not fall within the EPL limitations that were addressed in this research, which eliminates the possibility of a dependency between the two variables.

Majority of the existing ships can be achieved the minimum CII rating viz. C by installing the EPL. EPL is a restriction to the maximum power output of the main engine. As a consequence, this results in slower operational speeds and reduced fuel consumption. In circumstances involving concerns for safety navigation, the restriction can be ignored. About 80% of the sample tanker ships required to reduce the attained EEXI below the required EEXI with an average of 21% as can be seen in Fig. 5. A reduction in engine power of 20–35% is technically possible, but the ship must still have the necessary reserve in order to navigate through rough seas and severe weather. Fleet owners and operators have a responsibility to investigate the operating profile of their fleets in order to determine what levels of EPL are safe and feasible and whether or not further EETs are necessary. In the event that a ship is compelled by circumstances to deviate from its agreed EPL, the impact must be monitored and reported to the ship's RO as well as the administration. Additionally, adequate proof may be required in order to report the restoration of the EPL. Besides, it will not be possible for the operator to just "switch off" the EPL in order to conform to the requirements of a charterparty. In addition, there is no opportunity for trial and error to be used in determining the optimal speed and, as a result, power limit. Because the restriction on the engine governor is set in stone, it is important to consider what will take place if it is realized that the domestic fleet is unable to meet the demands of domestic trade.

The owners are responsible for considering the effects that the decisions they make about compliance will have on the security of the operation of their boats. When power is reduced, there will inevitably be a corresponding drop in manoeuvrability. Shipowners need to be confident that they can lower the overall amount of available power on their ships without compromising the safety margins that are now in place on such ships. At this moment, it is uncertain if an evaluation in accordance with IMO standards for establishing minimum propulsion power will be necessary when applying for an EPL. This is because the criteria have not yet been finalized. It is also unknown if there will be a precise 'down limit' on EPL, despite the fact that decreases cannot be endless due to safety concerns.

However, it is essential for each owner and operator of a tanker to be certain that a decrease in the tanker's propulsion power does not put at risk the safety of the people on board or the goods they are transporting. There will be situations in which the adoption of an EPL will not be adequate to accomplish the mandated EEXI and, at the same time, fulfil

Table 2
CO_2 reduction required for 10 sample tanker ships to reach the rating C of CII.
Source: Author's own elaboration from compilation database.

Domestic vessel	T16	T14	T19	T17	T18	T15	T12	T13	T10	T11
Age of ship	**11**	**13**	**14**	**14**	**14**	**15**	**15**	**15**	**16**	**16**
GT	**5698**	**5353**	**7920**	**7920**	**7920**	**5353**	**5081**	**5081**	**5081**	**5081**
DWT (t)	**8876**	**7990**	**9969**	**9998**	**9999**	**7990**	**7370**	**7361**	**7296**	**7301**
ME_{MCR} (kW)	**2814**	**2445**	**3310**	**3310**	**3310**	**2431**	**2574**	**2574**	**2574**	**2574**
2023	**B**	**B**	**E (Req. 19% CO_2 reduction)**	**E (Req. 40% CO_2 reduction)**	**E (Req. 33% CO_2 reduction)**	**C**	**D**	**D**	**E (Req. 23% CO_2 reduction)**	**E (Req. 49% CO_2 reduction)**
2024	**B**	**B**				**C**	**E (Req. 17% CO_2 reduction)**	**E (Req. 17% CO_2 reduction)**		
2025	**B**	**B**				**C**				
2026	**C**	**B**				**C**				
2027	**C**	**B**				**C**				
2028	**C**	**C**				**D**				
2029	**C**	**C**				**D**				
2030	**C**	**C**				**D (Req. 21% CO_2 reduction)**				
2031	**C**	**C**								
2032	**D**	**C**								
2033	**D**	**C**								
2034	**D (Req. 12% CO_2 reduction)**	**D**								
2035		**D**								
2036		**D (Req. 7% CO_2 reduction)**								
2037										
2038										
2039										
2040										

Table 3
CO_2 reduction required for 5 sample container ships to reach the rating C of CII.
Source: Author's own elaboration from compilation database.

Domestic vessel	C2	C3	C1	C4	C5
Age of ship	**17**	**17**	**19**	**26**	**26**
GT	**8724**	**9689**	**8766**	**11,810**	**13,448**
DWT (t)	**12,171**	**13,177**	**11,200**	**15,640**	**17,224**
ME_{MCR} (kW)	**3996**	**3996**	**5832**	**7704**	**8664**
2023	**A**	**A**	**B**	**B**	**B**
2024	**A**	**A**	**B**	**B**	**B**
2025	**A**	**A**	**B**	**C**	**B**
2026	**A**	**A**	**B**	**C**	**C**
2027	**B**	**A**	**B**	**C**	**C**
2028	**B**	**B**	**C**	**C**	**C**
2029	**B**	**B**	**C**	**C**	**C**
2030	**B**	**B**	**C**	**C**	**C**
2031	**B**	**B**	**C**	**D**	**D**
2032	**C**	**B**	**C**	**D**	**D**
2033	**C**	**C**	**D**	**D (Req. 9% CO_2 reduction)**	**D (Req. 4% CO_2 reduction)**
2034	**C**	**C**	**D**		
2035	**C**	**C**	**D (Req. 11% CO_2 reduction)**		
2036	**C**	**C**			
2037	**D**	**D**			
2038	**D**	**D**			
2039	**D (Req. 3% CO_2 reduction)**	**D (Req. 6% CO_2 reduction)**			
2040					

the commercial and safety criteria that are imposed on the ship. These scenarios are expected to occur. In order for a ship to remain both commercially viable and operationally safe, it is necessary to study the optimal combination of EPL and energy efficiency technologies.

The implementation of EPL is an easy approach for lowering carbon dioxide emissions because the amount of change that is required is quite little. However, its effectiveness is dependent on the operating power of the ship. A low operational power, such as that caused by sluggish steaming, is a disadvantage for the efficacy of EPL's reduction process. When an EPL is implemented, another problem that may arise is an increase in the expenses associated with maintenance. The industry is well aware of the extremely negative effects that can be caused on

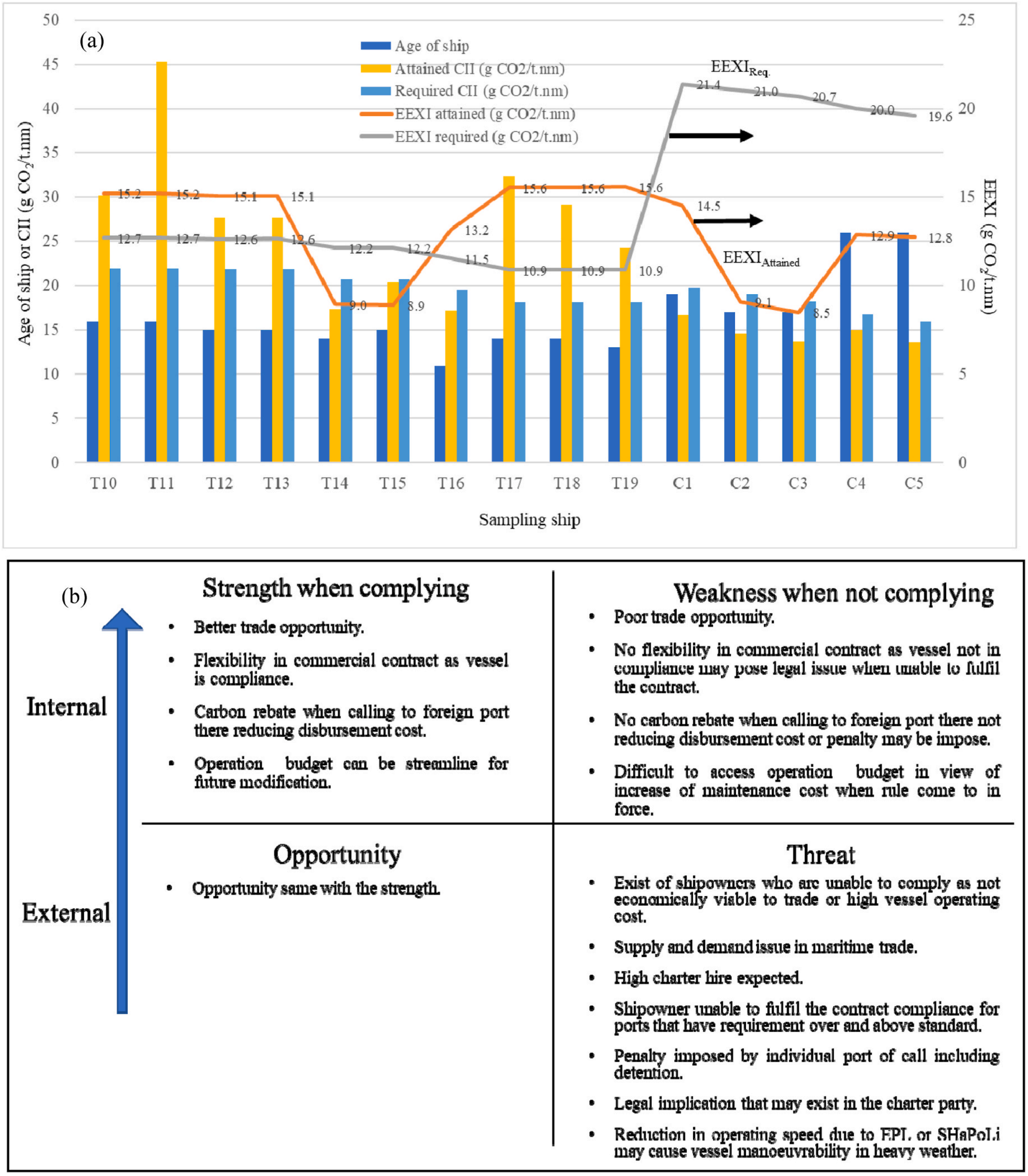

Fig. 5. a) Age, CII and EEXI of 15 sample ships in 2023 and b) SWOT analysis for the impact assessment with evidence-based on cost-effectiveness of IMO's EEXI and CII measures for decarbonizing Malaysian-registered domestic ships.
Source: Author's own elaboration from compilation database.

engines and components by operating an engine at a power level that is lower than the level at which it was designed to operate, as well as the additional maintenance and spare parts that may be required as a result of this. Shipowners have a responsibility to educate themselves on the ramifications of an EPL and determine whether or not an investment in EETs would be profitable. A ship must strike a balance between complying with the requirements and maintaining its capacity to make a profit in order to be able to apply an EPL decrease and continue to trade at charterparty speeds. Tanker owners may need to enter into re-negotiations with their clients in the case of long-term charter agreements. These renegotiations would be based on the speeds that are established by the charterparty. Communication between the shipowner and charterer will be more crucial than ever before in light of the fact that a direction from the charterer to increase the pace of the ship might lead to the ship falling out of compliance with the regulations.

The VA is an operational option that entails slowing down when it is anticipated that there may be a delay reaching the target port. This approach results in a longer period spent travelling over the ocean at a slower average speed, and as a result, a greater energy efficiency without changing the total amount of time spent travelling. Among the compliance option, operational compliance options are more preferred by the shipowners due to easy to install (EPL) and low investment costs (VA for Ships with long anchorage times, but low reduction potential for tanker and container ships). The WHRS have a significant amount of opportunity for decreasing the carbon dioxide but low cost-effectiveness. (Table S2). Sadly, this comes at the expense of hefty capital expenses, which in turn leads to lengthy payback times.

Shipowners are required to take action in accordance with the minimal compliance standards established by the IMO's short-term measures if their ship receives a rating of Label D for 3 years in a row or an E rating. In the event that no decision is made, it is presumed that a cut will be implemented for the year that follows. This objective can be accomplished by decreasing the CII value until it reaches a point that is equivalent to the upper limit of the Label C zone. When there are alternatives with extensive payback periods, one's age might become a deciding factor in whether or not they comply. Through the examined options, 70% of the sampling tanker ships cannot comply even not feasible (not commercially viable) if install with EPL due to long payback periods (Table S3). In addition, return of investment is based on future projector charter hire rate as against the ship operating expense. Ship operating expense, more less can be consistence if they are no major impact on the new EEXI requirement going forward. Referring to market availability for the ship to operate (estimated), ship trading requirement or expectancy will be based on the consecutive SEEMP part IV requirement going forward in which there is a possibility that to achieve reduce carbon emission may result in ship service's speed compromising the safety of the ship at passage or new technologies required may not be economically feasible resulting in the ship not being viable for trading. Hypothetically speaking, viability of the ship's trading or operation may be around less than 5 years. In terms of commercial implication, reduction of speed will impact charterer contract and employment. Reduction of speed will impact safety of ship. Bare chartered will complicate commercial matters during the period of compliance and charter party warranty speed & consumption. Because of this, the shipowner is faced with two choices viz. either implementing solutions that were not studied in this study, such as alternate fuels, or either scrapping the ship. If opt to first choice, the question of whether it is financially feasible to do so gets much more complicated when one considers that the typical lifespan of a ship is 25 years and that the payback times for some solutions might be rather extensive. The ships are sister ships (T10, T11, T12 and T13) equipped with similar technical devices. The externally managed T12 and T13 exhibit a slightly better CII rating than T10 and T11, which is managed internally. The only difference that can be seen between the two sets of data is that T10 and T11 have a load distribution that leans more heavily toward lower loads. There is not a shred of evidence to suggest that this is the result of alternative management systems.

On the basis of the data obtained, further suitable strategies may be devised in order to optimise strengths, reduce weaknesses, capitalise on opportunities, and defend against dangers. However, despite all of the aforementioned benefits, the subjectivity and linguistic character of SWOT analysis is regarded to be this method's primary flaw. As a result, it might be difficult to analyse the strategic aspects and evaluate the many plans that have been chosen. The SWOT analysis for assessing the effects using evidence-based on cost-effectiveness of IMO's EEXI and CII measures for decarbonizing Malaysian-registered domestic ships is summarized in Fig. 5, which can be seen here.

5. Conclusion and future research

Four different research questions were answered by the study. In order to accomplish this goal, the real operating data of 24 sample ships of varying sizes and ages were investigated. Out of 474 ship type specific with 400 GT and more, only 142 ships are plying in domestic waters. The sample ships representativeness is insufficient as about 50% represents the shipowner of domestic tanker and container ships for drawing general conclusions. As a result, the findings that are presented here need to be interpreted with some measure of constraint before they may be generalized. Significant repercussions await ship owners and operators as a result of the instruments developed by the IMO to cut carbon emissions and intensity. The owners of tanker ships are coming to the realization that the EEXI presents considerable hurdles to the commercial, technical, and safety elements of their ship operations. It is clear from the performance of the sample ships with regard to the IMO short-term measures that compliance is an expensive endeavour for the sample ships. This is the case for ships that are older or that have not implemented a number of compliance options that fall within the CII grade. Due to the nature of their construction, older ships are more susceptible to a variety of challenges. If already-operating domestic ships are to be brought into compliance, then the economic viability of the proposal must take centre stage. The EEXI does not favour on current domestic tanker ships because of their huge main engines, which allow them to operate at low engine loads. As a result, the current sample ships are capable of complying with the EEXI through the EPL by increasing their total amount of time spent at sea. The impacts that are imposed on shipowners and operators for compliance with the operational CII for their old ship are creating financial losses for them because the payback period of the required solutions is likely to exceed the lifetime of the ships, and, last but not least, scrapping these ships may be a widely adopted solution to this problem. These impacts were created for the purpose of compliance with the operational CII. It is difficult to estimate the whole impact that this has had on the fleet, but some people are already making projections about how many ships are likely to be scrapped as a result. Even if it is possible to bring an asset back into service, it may not be possible to do so in a manner that generates a profit or complies with applicable regulations. In these situations, it may be more prudent to scrap the asset rather than run the risk of having it become a stranded asset. This is especially true for older tankers.

A comparison based on a single criterion, such as age, might be made between the sample ships' capacities. There is no impact from the ship's capacity on either the required emission reductions or the reduction potential of the options that were investigated. The same is true for the management arrangements, whose sole influence is an indirect effect through the primary engine load profile, which is what decides how well EPL works. Indirect impacts were also shown to exist between age and the needs for a decrease in emissions, specifically through the design & technology vintages and the selection of technical choices to be implemented. For the already operating fleet of domestic tanker ships, options with protracted payback periods are not attractive. It is proposed that, for the sake of future study, additional consideration be given to the various types of ships, and the number of sample ships should be increased. Second, the incorporation of additional compliance alternatives, such as air lubrication and alternate fuels, is required.

Author contribution statement

Lai Fatt Chuah: Conceptualization; Formal analysis; Writing –original draft. Kasypi Mokhtar: Formal analysis; Investigation; Writing – review & editing. Siti Marsila Mhd Ruslan: Data curation; Writing-original draft. Anuar Abu Bakar: Conceptualization; Writing-original draft. Mohd Azhafiz Abdullah: Writing – review & editing. Nor Hasni Osman: Methodology; Software; Writing – review & editing. Awais Bokhari: Methodology; Visualization; Writing – review & editing. Muhammad Mubashir: Software; Investigation; Writing – review & editing. Pau Loke Show: Project administration; Resources; Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgements

The authors gratefully acknowledge the Malaysia's Ministry of Higher Education (MOHE), Malaysia Shipowners' Association, Marine Department Malaysia, Universiti Malaysia Terengganu (UMT) and Universiti Utara Malaysia (UUM). Heartfelt appreciation to Mohamed Safwan Othman, Captain Mohamad Halim Ahmed, Dato' Hj. Baharin Bin Dato' Abdul Hamid, Captain Abdul Samad Shaik Osman, Mohd Azhar Mohd Amin, Nor Izawaty Md Nor, Audi Zharif Aizat Ismail, Mohd Aiman Shihabudin, Adam Azman, Astuty Arshad, Noor Syazwani Zulkifli, Sheikh Alif, Dr. Wan Nurdiyana, Dr. Nur Hafiza, Mohd Hafizi, Dr. Loy Kak Choon, Dr. Chong Nyuk Sian, Tan Lee Chwin, Chew Kuan Lian, Teh Bee Bee, Loh Chong Hooi, Timmy Chuah Tim Mie and Ong Shying Weei for their support.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envres.2023.115348.

References

Asif, S., Ahmad, M., Bokhari, A., Chuah, L.F., Zafar, M., Sultana, S., Mir, S., 2019. Chemical conversion in biodiesel refinery. In: Rastegari, A., Yadav, A., Gupta, A. (Eds.), Prospects of Renewable Bioprocessing in Future Energy Systems. Biofuel and Biorefinery Technologies, vol. 10. Springer, Cham, pp. 201–217. https://doi.org/10.1007/978-3-030-14463-0_7.

Bokhari, A., Yusup, S., Asif, S., Chuah, L.F., Michelle, L.Z.Y., 2020. Process intensification for the production of canola-based methyl ester via ultrasonic batch reactor: optimization and kinetic study. In: Singh, L., Yousuf, A., Mahapatra, D.M. (Eds.), Bioreactors Sustainable Design and Industrial Applications in Mitigation of GHG Emissions. Elsevier Inc, pp. 27–42. https://doi.org/10.1016/B978-0-12-821264-6.00003-6.

Bokhari, A., Yusup, S., Chuah, L.F., Kamil, R.N.M., 2016. Relative efficiency of esterified rubber seed oil in a hydrodynamic cavitation reactor and purification via distillation column. Chem. Eng. Trans. 52, 775–780. https://doi.org/10.3303/CET1652130.

Bokhari, A., Yusup, S., Faridi, J.A., Kamil, R.N.M., 2014. Blending study of palm oil methyl esters with rubber seed oil methyl esters to improve biodiesel blending properties. Chem. Eng. Trans. 37, 571–576.

Bouman, E.A., Lindstad, E., Rialland, A.I., Strømman, A.H., 2017. State-of-the-art technologies, measures, and potential for reducing GHG emissions from shipping - a review. Transp. Res. D Transp. Environ. 52, 408–421.

Cheah, K.W., Yusup, S., Chuah, L.F., Bokhari, A., 2016. Physio-chemical studies of locally sourced non-edible oil: prospective feedstock for renewable diesel production in Malaysia. Procedia Eng. 148, 451–458.

Chuah, L.F., Bokhari, A., Asif, S., Klemeš, J.J., Dailin, D.J., Enshasy, H.E., Yusof, A.H.M., 2022a. A review of performance and emission characteristic of engine diesel fuelled by biodiesel. Chem. Eng. Trans. 94, 1099–1104. https://doi.org/10.3303/CET2294183.

Chuah, L.F., Bokhari, A., Yusup, S., Saminathan, S., 2017. Optimisation on pretreatment of kapok seed (*Ceiba pentandra*) oil via esterification reaction in an ultrasonic cavitation reactor. Biomass Conv. Bioref. 7, 91–99. https://doi.org/10.1007/s13399-016-0207-9.

Chuah, L.F., Chew, K.W., Bokhari, A., Mubashir, M., Show, P.L., 2022b. Biodegradation of crude oil in seawater by using a consortium of symbiotic bacteria. Environ. Res. 213, 113721 doi.org/10.1016/j.envres.2022.113721.

Chuah, L.F., Klemeš, J.J., Bokhari, A., Asif, S., Cheng, Y.W., Chong, C.C., Show, P.L., 2022c. A review of intensification technologies for biodiesel production. In: Gutierrez-Antonio, C., Gomez Castro, F.I. (Eds.), Biofuels and Biorefining. Volume 2: Intensification Processes and Biorefineries. Elsevier Inc, pp. 87–116. https://doi.org/10.1016/B978-0-12-824117-2.00009-0.

Chuah, L.F., Mokhtar, K., Abu Bakar, A., Othman, M.R., Osman, N.H., Bokhari, A., Mubashir, M., Abdullah, M.A., Hasan, M., 2022d. Marine environment and maritime safety assessment using Port State Control database. Chemosphere 304, 135245 doi.org/10.1016/j.chemosphere.2022.135245.

Chuah, L.F., Klemes, J.J., Bokhari, A., Asif, S., 2021a. A review of biodiesel production from renewable resources: chemical reactions. Chem. Eng. Trans. 88, 943–948. https://doi.org/10.3303/CET2188157.

Chuah, L.F., Mohd Salleh, N.H., Osnin, N.A., Alcaide, J.I., Abdul Majid, M.H., Abdullah, A.A., Bokhari, A., Jalil, E.E.A., Klemes, J.J., 2021b. Profiling Malaysian ship registration and seafarers for streamlining future Malaysian shipping governance. Aust. J. Marit. Ocean. Aff. 13 (4), 225–261.

Chuah, L.F., Abd Aziz, A.R., Yusup, S., Bokhari, A., Klemeš, J.J., Abdullah, M.Z., 2015. Performance and emission of diesel engine fuelled by waste cooking oil methyl ester derived from palm olein using hydrodynamic cavitation. Clean Technol. Environ. Policy 17 (8), 2229–2241.

Guan, C., Theotokatos, G., Chen, H., 2015. Analysis of two stroke marine diesel engine operation Including turbocharger cut-out by using a zero-dimensional model. Energies 8, 5738–5764.

Irena, K., Ernst, W., Alexandros, C.G., 2021. The cost-effectiveness of CO_2 mitigation measures for the decarbonisation of shipping. The case study of a globally operating ship-management company. J. Clean. Prod. 316, 128094. Doi.org/10.1016/j.jclepro.2021.128094.

Mallouppas, G., Yfantis, E.A., 2021. Decarbonization in shipping industry: a review of research, technology development, and innovation proposals. J. Mar. Sci. Eng. 9 (415), 1–40. https://doi.org/10.3390/jmse9040415.

Malik, S., Fatima, F., Imran, A., Chuah, L.F., Klemes, J.J., Khaliq, I.H., Asif, S., Aslam, M., Jamil, F., Durrani, A.K., Akbar, M.M., Shahbaz, M., Usman, M., Atabani, A.E., Naqvi, S.R., Yusup, S., Bokhari, A., 2019. Improved project control for sustainable development of construction sector to reduce environment risks. J. Clean. Prod. 240, 118214. https://doi.org/10.1016/j.jclepro.2019.118214.

Mukhtar, A., Saqib, S., Mellon, N.B., Rafiq, S., Babar, M., Ullah, S., Muhammad, N., Khan, A.L., Ayoub, M., Ibrahim, M., Maqsood, K., Bustam, M.A., Al-Sehemi, A.G., Klemeš, J.J., Asif, S., Bokhari, A., 2020. A review on CO2 capture via nitrogen-doped porous polymers and catalytic conversion as a feedstock for fuels. J. Clean. Prod. 277, 123999.

Nawaz, S., Ahmad, M., Asif, S., Klemeš, J.J., Mubashir, M., Munir, M., Zafar, M., Bokhari, A., Mukhtar, A., Saqib, S., Khoo, K.S., Show, P.L., 2022. Phyllosilicate derived catalysts for efficient conversion of lignocellulosic derived biomass to biodiesel: A review. Biores. Technol. 343, 126068.

Psaraftis, H.N., Zis, T., Lagouvardou, S., 2021. A comparative evaluation of market based measures for shipping decarbonization. Maritime Transport Res 2, 100019. Doi.org/10.1016/j.martra.2021.100019.

Rutherford, D., Mao, X., Osipova, L., Comer, B., 2020. Limiting engine power to reduce CO_2 emissions from existing ships. Available: https://theicct.org/publication/limiting-engine-power-to-reduce-co2-from-existing-ships/. (Accessed 17 October 2022). Accessed.

Schroer, M., Panagakos, G., Barfod, M.B., 2022. An evidence-based assessment of IMO's short-term measures for decarbonizing container shipping. J. Clean. Prod. 363, 132441. Doi.org/10.1016/j.jclepro.2022.132441.

Tawfik, A., Nasr, M., Galal, A., El-Qelish, M., Yu, Z., Hassan, M.A., Salah, H.A., Hasanin, M.S., Meng, F., Bokhari, A., Qyyum, M.A., Lee, M., 2021. Fermentation-based nanoparticle systems for sustainable conversion of black-liquor into biohydrogen. J. Clean. Prod. 309, 127349.

Yusup, S., Bokhari, A., Chuah, L.F., Ahmad, J., 2015. Pre-blended methyl esters production from crude palm and rubber seed oil via hydrodynamic cavitation reactor. Chem. Eng. Trans. 43, 517–522.

Further reading

Henriksson, D., Vierto, R.N., 2016. Exhaust Gas Economizer on Auxiliary Engines. Department of Shipping and marine technology. Chalmers University of Technology, Gothenburg. Sweden.

Jia, H., Adland, R., Prakash, V., Smith, T., 2017. Energy efficiency with the application of virtual arrival policy. Transp. Res. D Transp. Environ. 54, 50–60.

Ship and Bunker, 2022. Global average bunker price. Available: https://www.shipandbunker.com/prices/av/global/av-glb-global-average-bunker-price#MGO. (Accessed 17 October 2022). Accessed.