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Systematic Review

Scientometric Analysis of Energy Efficiency Indicators in Maritime Transportation: A Systematic State-of-the-Art Review and Implications

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Abstract: This study investigates energy efficiency indicators including the Energy Efficiency Design Index (EEDI), Energy Efficiency Operational Index (EEOI), Ship Energy Efficiency Management Plan (SEEMP), Energy Efficiency Existing Ship Index (EEXI), and Carbon Intensity Indicator (CII) by providing a comprehensive scientometric analysis. The specified indices are scrutinized using papers from WoS and Scopus databases by applying the Preferred Reporting Items for Systematic Reviews and Meta Analyses (PRISMA) method to select the most appropriate papers in the related literature. Keyword and citation analysis of papers were performed using the VOSviewer software program to reveal the current research trends. The analysis addresses several critical aspects. Firstly, it focuses on identifying which indicators are employed more frequently in the literature, and secondly, it classifies the research according to whether a calculation was made, and the yearly distribution was determined. The results pinpoint that the EEDI and EEOI were examined in 42.55% and 22.49% of the reviewed studies, respectively. Furthermore, it is evident that the EEXI and CII percentages have increased drastically over the past three years, with the figures standing at 20.01% and 18.59%, respectively. Consequently, in alignment with the findings, the theoretical and managerial implications are highlighted for the private sector, academia, and maritime stakeholders.

Keywords: maritime transportation; energy efficiency; critical review; PRISMA; VOSviewer; EEDI; EEOI; SEEMP; EEXI; CII

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1. Introduction

The International Maritime Organization (IMO) plays a significant role in performing sustainable development goals since it is responsible for the safety and security of maritime transportation as well as the air and sea pollution caused by ship-related activities. The responsibilities created by the IMO are quite critical for global sustainability because most global trade is carried out via maritime transport [1].

Sustainable development goals have been categorized under 17 fundamental headings, and the advancements in maritime transportation have the potential to make great noteworthy contributions to several of the items under these headings and sub-headings [2]. Substantial technical, operational, and alternative initiatives have been implemented such as providing energy efficiency or searching for the best optimal alternative fuel to mitigate the climate change caused by maritime shipping [3]. These efforts are directly associated with most of the main headings within the sustainable development goals.

In the context of energy efficiency measures, the Energy Efficiency Operational Index (EEOI) has been introduced and its voluntary implementation was suggested in 2009. Then, it evolved to monitor the energy efficiency under the Ship Energy Efficiency Management Plan (SEEMP) Part I [4]. The Energy Efficiency Design Index (EEDI) and the SEEMP entered into force at the beginning of 2013 in the first phase. Although the SEEMP does not function as an indicator, it is a significant operational mechanism for providing the cost-effective operation of ships and the enhancement of energy efficiency.

The primary objective of these measures is to enhance energy efficiency and reduce greenhouse gas (GHG) emissions across the global maritime fleet as significantly as feasible. Considering the performed efforts, the maritime authorities have set a target to decrease the carbon intensity in maritime transportation by 40% by the year 2030 compared to the year 2008. In addition to the EEDI and SEEMP, the Energy Efficiency Existing Ship Index (EEXI) and Carbon Intensity Indicator (CII) entered into force after 1 January 2023. The EEXI and CII have encompassed technical and operational measures to achieve the future GHG target set by the IMO [5].

Under the revised GHG reduction strategy, the IMO has aimed to eliminate GHG emissions by up to 70% by 2040 and even try to reduce them to 80% by increasing the efforts. By the year 2050, GHG emissions originating from maritime transportation are planned to be eliminated to reach net-zero emissions which holds eminence for both the sustainability of maritime transportation and the well-being of our Earth [6,7].

Energy efficiency-saving applications on marine vessels are quite critical for sustainable maritime transportation [8,9]. Therefore, maritime authorities put substantial efforts into providing energy efficiency savings through revealing indexes.

Many studies and reports on these indexes have been published because ships which do not comply with this necessity of indexes will make it quite challenging for the ship owners and operators in the phase of performing commercial activities. The specified indexes have been comprehensively described and classified under the determined criteria. To the best of the authors' knowledge, no study has been found in the literature conducting a specified methodology.

The main motivation of the study is to reveal the current research trends and applications and provide a critical discussion in the light of the specified indexes which are the CII, EEDI, EEOI, EEXI, and SEEMP, respectively. More than five indicators have been presented by the maritime authorities up to now, especially the five main indicators mostly brought to the forefront by the IMO and academicians within the scope of providing more efficient and sustainable maritime transportation.

The fundamental aim of the study is to classify the related studies based on these five indicators with their qualifications such as published year, paper type, separation, and calculation considering all the studies' examination of the energy efficiency indexes.

The remainder of the paper is organized as follows. The energy efficiency measures, methodology, results, and discussion of the study are described in Section 2, Section 3, Section 4, and Section 5, respectively. Lastly, the conclusion and future research opportunities are explained in Section 6.

2. Indicators of the Energy Efficiency Measures

On 1 January 2013, the SEEMP, EEDI, and EEOI came into effect [10]. For over a decade, these policies have been driving improvements in the energy efficiency across the global fleet; they represent the first globally required GHG reduction regime for an international industry sector [11]. The EEXI and CII, which took effect on 1 January 2023, are two new technical and operational metrics that the IMO adopted in 2021 [12].

2.1. Ship Energy Efficiency Management Plan

An operational planning tool for enhancing a ship's environmental performance at a reasonable cost is defined as the SEEMP which strongly advises the ship owner and operator to take innovative practices and technology into account at every level of the plan [13,14].

Using the approved monitoring technologies, the SEEMP offers maritime businesses a method for managing the efficient performance of their fleet and ships over time [5,15]. The most effective methods for operating fuel-efficient ships are incorporated into the 2022 guidelines for the development of the SEEMP, along with templates for the creation of SEEMPs, which should consist of three parts [5,13]:

- Energy-efficient ship management strategy.
- Plan for gathering data on ship fuel oil usage.
- Carbon Intensity Plan for Ship Operations.

2.2. Energy Efficiency Design Index

The EEDI is a significant technical initiative that encourages the use of more energy-efficient machinery and engines in the construction of new ships to reduce their environmental impact. For various ship types and size segments, the EEDI mandates a minimum energy efficiency level per capacity and mile [5].

EEDI is a flexible, performance-oriented approach that allows the option of technologies to be deployed in an individual vessel's construction for industry. The most economical methods for the ship to abide by the requirements may be used by designers and builders as long as the necessary energy efficiency level is reached [16]. The concept formula to calculate the EEDI is given in Equation (1) [11].

$$\mathrm{EEDI} = \frac{\mathrm{C_F} \times \mathrm{SFC} \times \mathrm{E}}{\mathrm{Capacity} \times \mathrm{V_{ref}}} \tag{1}$$

The carbon coefficient (C_F) of the fuel was obtained from the guideline published by the IMO [17]. SFC in the formula represents the specific fuel consumption in g/kWh, and E is the energy generated by the main engine in kWh. The capacity can be taken as deadweight tonnages (DWTs) or gross tonnages regarding the ship type. V_{ref} is the reference vessel velocity in knots which can be found by using various methods depending on the availability of information such as operational data and performance curves or empirical calculation [17].

2.3. Energy Efficiency Operational Index

A tool for calculating carbon dioxide (CO_2) gas emissions based on transportation work is presented as the EEOI which illustrates the real transport effectiveness of a ship while it is in service [18]. The navigational factors such as temperature and wind direction have a considerable impact on the EEOI of each voyage, making the long-term measurement of a ship's energy efficiency challenging [15]. The calculation of the EEOI can be ensured by employing Equation (2) [15,18].

$$\mathrm{EEOI} = \frac{\mathrm{C_F} \times \sum \mathrm{FC}}{\mathrm{Distance} \times \mathrm{m_{cargo}}} \tag{2}$$

The FC represents the total mass of consumed fuel during the voyage, m_{cargo} is the transported cargo weight or work such as passengers or amount of twenty-foot equivalent units. The distance indicates the traveled nautical miles while carrying the cargo [15].

2.4. Energy Efficiency Existing Ship Index

The EEXI has replaced the EEDI, and the main discrepancy between them is the application of the reduction factor [19]. The computation of "attained EEXI" can be conducted by using Equation (1) [20]. The EEXI measures the ship's "technical" or "design" efficiency, which must be calculated by all current ships of 400 GT and higher [5]. Technologies such as waste heat recovery, wind-assisted propulsion, and engine/shaft power limitation are already in place to help meet the requirements of the "required EEXI". The "required EEXI" can be calculated by utilizing Equation (3) [21].

$$\text{Required EEXI} = \left(1 - \frac{X}{100}\right) \times \text{EEDI Reference Line} \quad (3)$$

The "EEDI Reference Line" is computed according to the ship's type and size [20]. Similarly, the reduction factor of EEXI (X) is determined differently for ships considering their DWT and type [21]. The "attained EEXI" must be lower than the "required EEXI" for the vessels [22].

2.5. Carbon Intensity Indicator

The CII is the enhanced version of the EEOI, and the most important differences are the reduction factors employed annually and the efficiency category determination between A and E named as the CII rating [23]. If a ship has received a D rating for three years in a row or an E rating for one year, it must submit an action plan for correction detailing how it will raise itself to the required index of C or higher [24].

It is recommended that government agencies, port authorities, and other relevant parties provide awards to ships that receive an A or B rating. For vessels that calculate the EEDI and are 5000 GT or more, the yearly CII application and ratings are required [19,25]. The calculation of the "attained CII" is the same as the EEOI computation shown in Equation (2). The "required CII" can be found by using Equation (4).

$$\text{Required CII} = \frac{100 - Z}{100} \times \text{CII}_{\text{Ref}} \quad (4)$$

The reduction factor for CII (Z) was decided at 5% in 2023, and the annual reduction of 2% is planned to be enforced [26]. The limits of ratings and reference CII (CII_{Ref}) are decided by utilizing comparisons dependent on the ship capacity and dimensionless coefficients as depicted in [27].

3. Methodology

Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) was employed to examine the papers systematically ranging from 2010 to the end of 2023. The PRISMA protocol first proposed in the literature provides researchers with a way to carry out studies in a detailed, logical, and clear way [28].

There are 4 main steps in the PRISMA protocol: identification, selection, eligibility, and inclusion. In the Identification step, the papers belonging to the selected databases related to the subject are revealed. Afterwards, the final number of papers is obtained in the selection section. In the eligibility section, the papers are examined in detail, and the papers that are not relevant to the subject are excluded. In conclusion, the final section of the document, entitled "inclusion", contains all the studies related to the subject, thus enabling the commencement of a comprehensive scientific analysis.

The protocol has the potential to help researchers reveal, select, and examine the most related studies in the current literature. Considering the contribution of the PRISMA protocol's benefits to the researchers, the PRISMA 2020 statement introduced in the literature has been employed to explore the current research trends in the literature on energy efficiency indicators [29].

The systematic energy efficiency indicators literature review has been conducted in three different steps:

- Creating unique research question(s);
- Adding identification, selection, eligibility, and inclusion criteria under the related research questions.
- Examining studies in several different and non-overlapping aspects.

Research questions based on the current literature were created in the first phase. Especially, energy efficiency came into prominence in maritime transportation considering the sustainable development goals (SDGs) and developing international regulations. In parallel with this purpose, the answers "What are the main energy efficiency indicators?" and "What are the current research trends on energy efficiency indicators?" were researched. Afterward, the identification, selection, eligibility, and inclusion criteria of the systematic review were revealed.

The investigated papers were obtained from two databases, which are Scopus and Web of Science (WoS). In the Scopus database, Title (TIT)-Abstract (ABS)-Keywords (KEY) as "(TITLE-ABS-KEY ("maritime") AND ("EEXI") OR ("EEDI") OR ("CII") OR ("SEEMP") OR ("EEOI"))" were searched. The specified filter meant that the paper must contain "maritime" with either the EEXI, EEDI, CII, SEEMP, or EEOI in their Title, Abstract, or Keywords section. On the other hand, papers that were acquired from the WoS database using Booleans and Field Tags were written down following "(TI = (maritime) or AB = (maritime) or AK = (maritime)) AND ((TI = (EEXI) or AB = (EEXI) OR AK = (EEXI)) OR (TI = (EEDI) or AB = (EEDI) OR AK = (EEDI)) OR (TI = (CII) or AB = (CII) OR AK = (CII)) OR (TI = (EEOI) or AB = (EEOI) OR AK = (EEOI)) OR (TI = (SEEMP) or AB = (SEEMP) OR AK = (SEEMP)))" in the advanced search sections of documents.

The specified search performed in the WoS database refers to the same method as the Scopus database, and no time limitations were applied in both databases. The systematic review procedure is explained under the terms of the PRISMA method in Figure 1.

The systematic review flowchart was conducted in four steps: (1) identification; (2) selection; (3) eligibility; and (4) inclusion in the first step. In the identification step, Scopus and the WoS databases were used to obtain the studies. A total of 229 and 150 studies were identified in the Scopus and the WoS database, respectively.

After excluding the studies that were not in the English language, the number of papers decreased to 221 and 147 in the Scopus and the WoS databases, respectively. Consequently, 368 studies were obtained in the energy efficiency indicators literature. In the second step, 137 duplicated papers obtained from both the WoS and the Scopus databases were removed.

Subsequently, 39 papers were also eliminated because they did not match the related scope, after examining the rest of the 231 papers. Finally, at the end of the applied PRISMA method, 192 papers were systematically selected within the scope of energy efficiency indicators. The following sections present the analysis results of the selected papers.

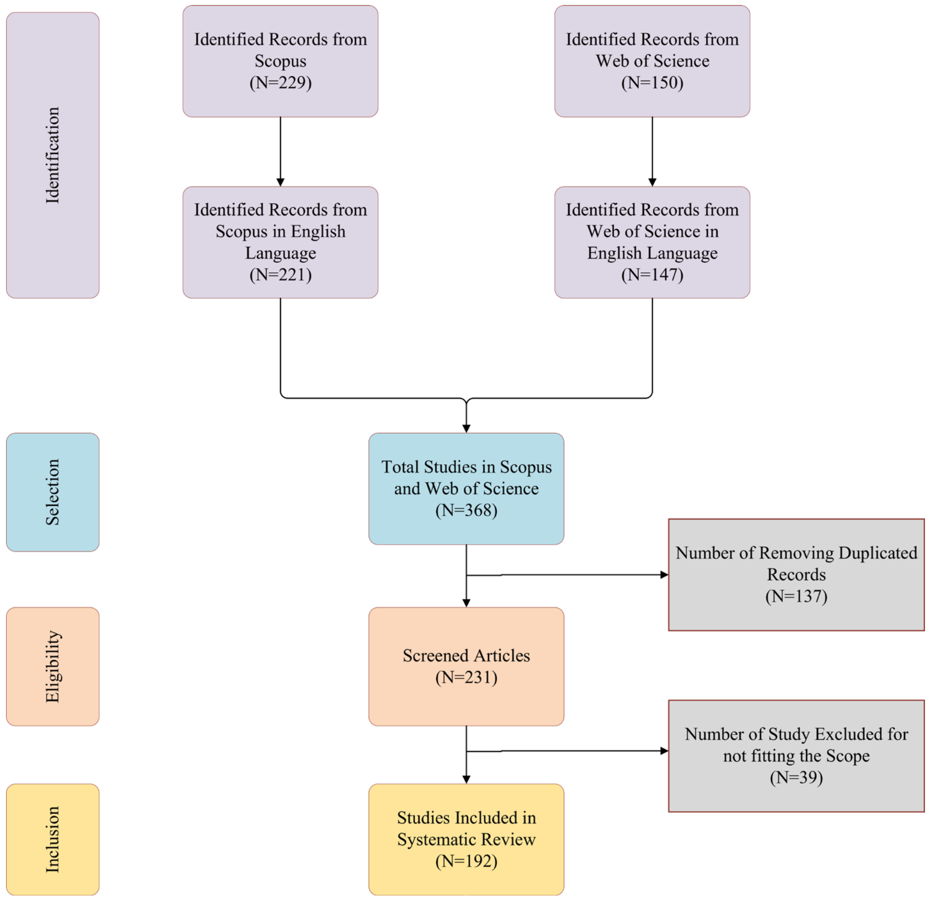

Figure 1. Systematic review flowchart under the PRISMA method.

4. Results

The analysis results of the systematic review are presented based on the energy efficiency literature in this chapter. The analysis results are presented twofold. Primarily, the VOSviewer 1.6.18 software results with a citation network of prominent authors and keyword analysis of the studies are given in Section 4.1.

The results of the comprehensive examination of 192 studies in the energy efficiency indicators literature are depicted in Section 4.2. Studies based on the EEDI, EEOI, EEXI, and SEEMP were assessed using very significant and unique methods. To the best of the authors' knowledge, no study in the related literature used a taxonomy referencing their paper, journal, country type, indicator calculation, separation and classification, and yearly distribution.

4.1. VOSviewer Visualization of Results

The VOSviewer software program was first introduced to provide researchers a means for revealing the scientific landscapes of the current academic literature [30]. The software program is widely accepted by scholars, and there are several different applications such as innovation adoption, green shipping practices, alternative marine fuels, maritime technology, route optimization in maritime transportation, maritime accidents, etc. [31–35]. The citation network of the energy efficiency indicators is demonstrated based on the literature in Figure 2.

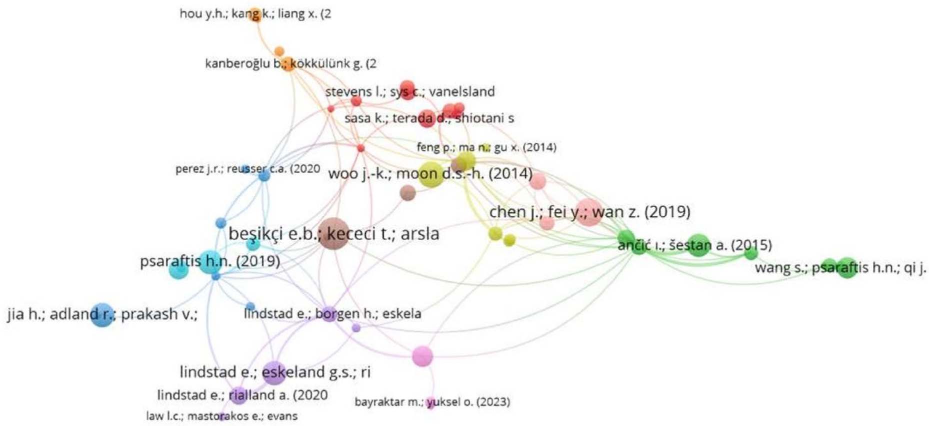

Figure 2. Citation network of studies [10,19,36–51].

According to Figure 2, Besikci et al. [36], Chen et al. [37], Woo and Moon [45], Lindstad et al. [46], and Psaraftis [47] are located near the center of the studies and have been highly cited among the others. In addition to these studies, Sprenger et al. [48] and Jia et al. [49] have also a considerable number of citations. Seven articles were examined in terms of their specific aim, and the study's contribution is presented in Table 1. The remaining articles displayed in the figure are referenced in the appendices.

Table 1. Examination of seven highly cited studies in the citation network.

Paper(s)	Aim of the Paper	Contribution of the Paper
[45]	To calculate the effects of slow steaming in liner shipping and investigate the link between trip speed and CO_2 emissions.	Slow steaming is excellent for lowering CO_2 emissions; however, it is not necessarily helpful for lowering the operational expenses.
[36]	To weigh and prioritize the ship's operational efficiency measures.	The authors revealed and prioritized the ship's operational efficiency measures to identify potential solutions.
[49]	To evaluate the 5066 voyages 483 Very Large Crude Carriers (VLCCs) completed between 44 countries in 2013 and 2015 and calculate the fuel savings that could occur if the idle waiting time at the destination ports is utilized to reduce the average sailing speed.	The outcomes demonstrate the significant reductions in fuel expenditures and emissions, which are crucial for policymaking and the improvement of trip management in shipping businesses.
[48]	The creation of appropriate techniques, instruments, and guidelines is the goal of this article to address the issues and promote safe and environmentally friendly shipping.	Propulsion and rudder force tests in waves raised resistance and drift forces at zero and moderate forward speeds, and the assessment of ship maneuverability in waves in comparison to calm water conditions is the key area of focus.
[37]	To investigate the connection between GHG emissions and fleet size.	Studies revealed that slowing steaming and the EEDI and EEOI reduced GHG emissions.
[47]	The study aimed to reveal the challenges of the decarbonization path.	The study revealed the difficulties and opportunities of the decarbonization process.
[46]	LNG was evaluated considering the decarbonization pathways in the maritime sector	While LNG as a marine fuel is a good option for mitigating GHGs, its reduction rate is limited. That is why zero-carbon fuel should be considered when the technical maturity has been accomplished in the maritime sector.

The keyword analysis of the examined papers in the related literature is demonstrated in Figure 3.

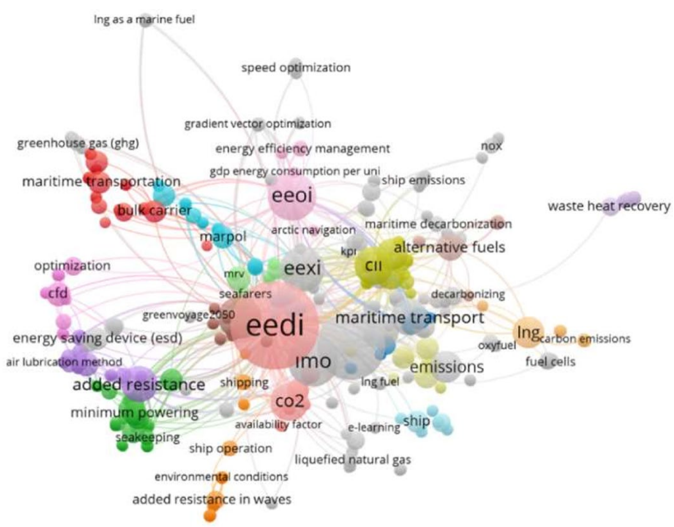

Figure 3. Keyword analysis.

As highlighted in Figure 3, the EEDI was found to be the most occurring keyword in the energy efficiency indicators literature and was repeated 63 times because both the EEDI and SEEMP were introduced as the first global mandatory GHG-reduction strategies for maritime transportation after these indexes entered into force at the beginning of 2013 [52]. Therefore, EEDI may have been examined in many studies throughout the last decade.

Under the investigated papers, the EEDI index has been mentioned with alternative fuels such as LNG and is related to the keywords, "energy saving", "optimization", "green ship", and more. Before the introduction of the CII in the year of 2019, the EEOI was used as an operational indicator for marine vessels. After the Verified Data Collection System data from marine vessels have been reported to the IMO, the CII of the ship has been calculated since 1 January 2019 [53]. That is why the EEOI has come to the fore in the literature review, especially until 2019, instead of the CII. As evidence of this situation, the EEOI has emerged as the second most frequently mentioned keyword, repeating a total of 19 times in the articles.

The EEOI has related to keywords such as "optimization", "ship operation", and "CO_2" for providing efficient ship operations. Although the EEXI entered into force on 1 January 2023 as a technical design requirement, it was repeated 16 times in the articles [53]. The SEEMP describes an operational mechanism created in a cost-effective manner to increase the energy efficiency of ships or fleets.

However, the SEEMP has been mentioned 15 times in the literature. The CII value and its rating have been utilized to calculate the operational energy efficiency of ships. The CII thresholds are being lowered every year at certain rates. Even though it is crucial to implement technologies that meet these restrictions on maritime vessels, the CII has been highlighted only 12 times, which is relatively little in the reviewed studies. In the subsequent section, examinations of the papers are deeply performed from various perspectives.

4.2. Deeper Analysis of the Results

A comprehensive review of the energy efficiency indicators has been undertaken in the literature within the realm of maritime transportation. Studies in the deeply examined literature have been presented and discussed from various perspectives. Firstly, studies are distributed yearly in Figure 4.

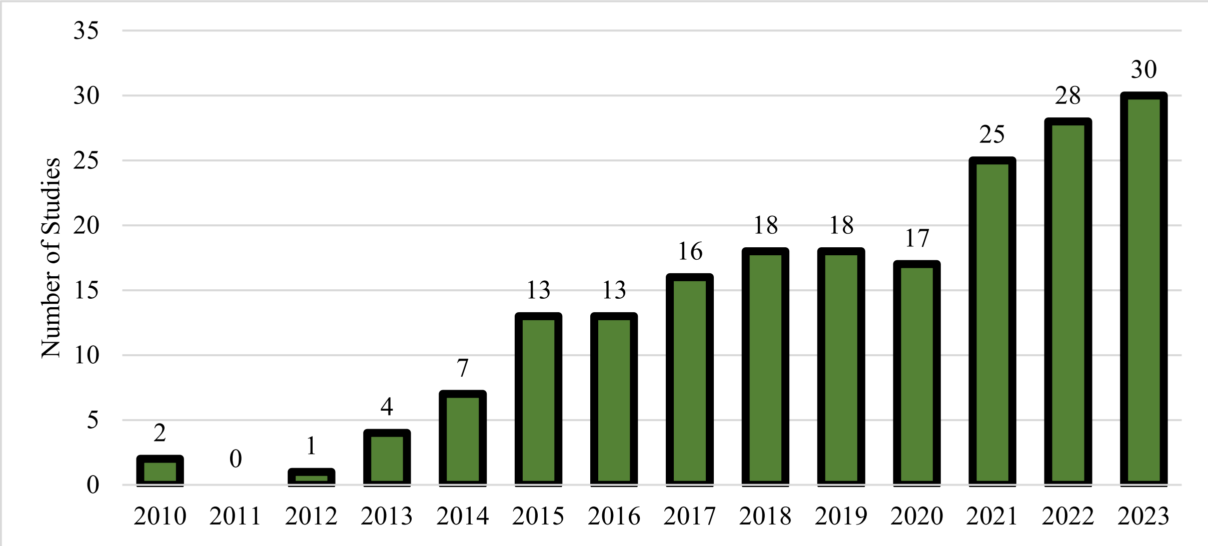

Figure 4. Yearly distribution of studies.

According to Figure 4, the first study in related literature was conducted in 2010. The IMO adopted amendments encompassing both technical and operational aspects under the MARPOL Annex VI in the year 2011 to enhance the energy efficiency applications that also reduce carbon emissions [1]. Hence, it is quite reasonable to perform research within this field using the energy efficiency indicators in the year 2010. The mandatory adaptation to the indexes and the need for energy efficiency applications triggered a noticeable rise in the number of studies as depicted in Figure 4, over the subsequent years. The authors are categorized based on the countries in which they conducted their studies in Figure 5.

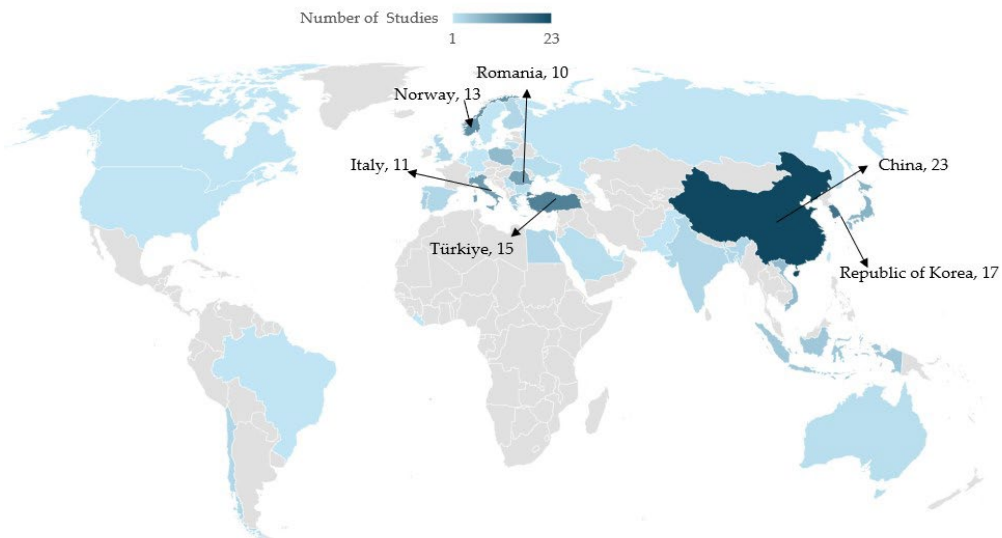

Figure 5. Country-based distribution of studies.

It is noteworthy that most of the studies were found to have been conducted in China, the Republic of Korea, Türkiye, Norway, and Italy when examining the literature on the energy efficiency indicators. In addition to these countries, Romania and Japan have also a considerable number of studies. Other countries such as Serbia, the Netherlands, Belgium, and Sweden that have 1 or 2 studies that have been depicted, and 33 studies have been conducted in these countries.

The substantial number of studies conducted in other countries serves as a shred of significant evidence that the research on these indicators is not limited to a specific region but is carried out across the world. The investigations have encompassed a total of 46 different countries, including other countries. In the following Figure 6, the publication types of the studies are presented as articles, conference papers, and book chapters.

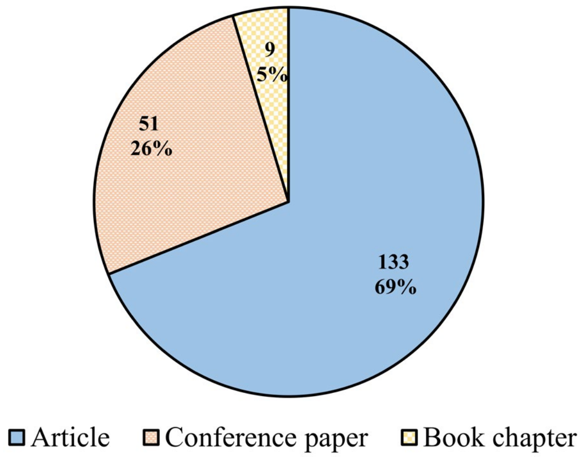

Figure 6. Publication distribution of studies.

According to Figure 6, the rate of articles of 69% and conference papers of 26% encompasses the related literature. The remaining 5% rate covers the book section. A total of 132 articles, corresponding to 69%, have been published by various academic journals. The distribution of indicators has been divided into three groups: one, two, and more than two indicators as depicted in Figure 7.

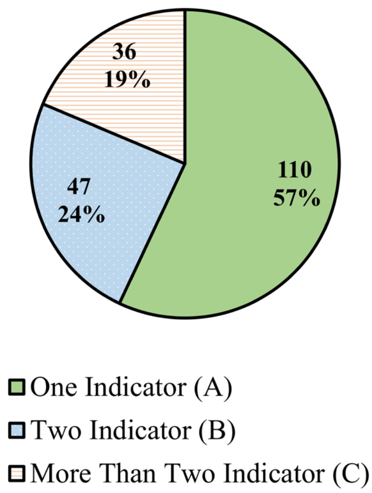

Figure 7. Indicator separation: (A) one indicator, (B) tow indicators, and (C) more than two indicators.

(A), (B), and (C) mean that the study reviewed, examined, or made calculations based on one, two, and more than two energy efficiency indicators, respectively. A total of 192 studies were subjected to a comprehensive and in-depth examination.

One indicator has been utilized in 109 papers. Two and more than two indicators have been used in the remaining studies, numbering 47 and 36, respectively. A deeper examination of each indicator's studies is given in Appendix A as Table A1 for the "One Indicator" cluster, Table A2 for the "Two Indicator" cluster, and Table A3 for the "More Than Two Indicator" cluster. The studies' specific aims and contributions are presented yearly. Figure 8 illustrates the distribution of indicators identified across the reviewed studies.

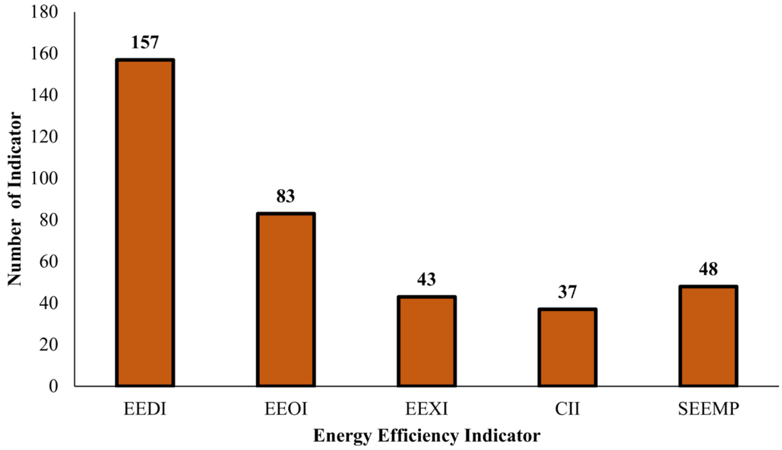

Figure 8. Number of indicator distribution.

As stated in the figure, a total of 345 indicators were stated and examined in the related literature. The most utilized indicator is the EEDI, a total of 142 times. The EEDI is followed by the EEOI, SEEMP, EEXI, and CII which are utilized 76, 47, 43, and 37 times, respectively, in the related literature.

The utilization of EEDI is quite common compared to the other indexes because EEDI was one of the first energy efficiency measures introduced, and EEDI is still used. The EEOI, the closest follower of the EEDI, has been examined approximately twice as much as the remaining indexes although the EEOI was replaced by the CII after the year of 2019. Despite the SEEMP being introduced concurrently with EEDI, it is comparatively less frequently employed in academic studies. Even though EEXI is a relatively recently introduced index, it has already been found in 43 studies.

There is a sign that the ranking of the EEXI's usage among the other indexes will probably rise in the upcoming years when considering academic studies. Despite being introduced in 2019, a notable number of studies have mentioned the CII up to 2023.

While some of the studies merely addressed the indicators, others performed calculations based on these indicators. Making calculations related to indicators is of utmost importance when assessing compliance with the reference values determined by the IMO. Furthermore, 52% (99) of the studies conducted a calculation of the indexes while the remaining 93 studies examined the metrics qualitatively. Figure 9 reveals the distribution of the calculated indicators.

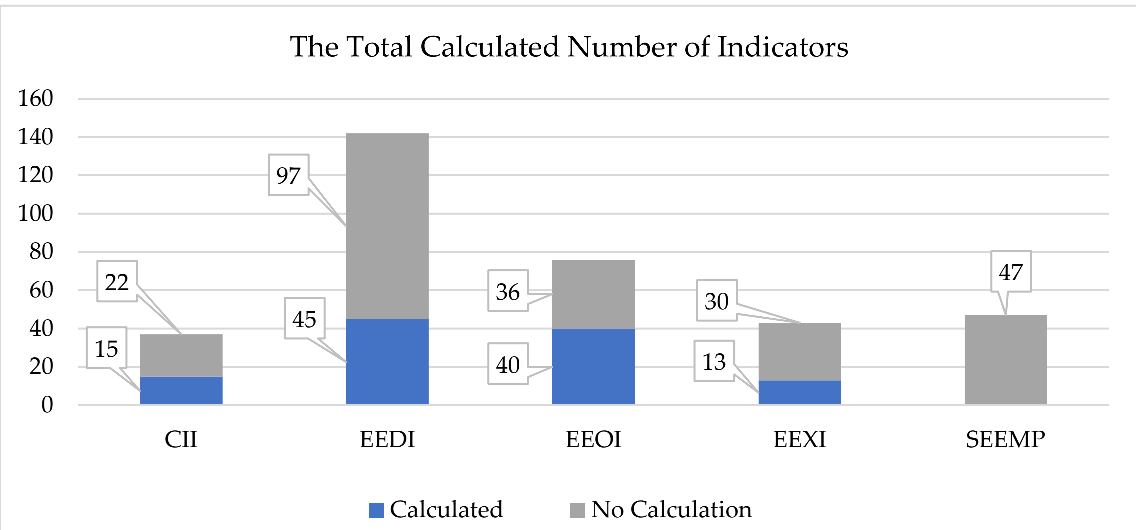

Figure 9. Calculated indicator distribution.

Since the EEDI and EEXI are technical measures, the calculation rate in the studies mentioning this indicator is 31% and 30%, respectively. Most studies address these indicators, even if calculations are not performed because the energy efficiency initiatives implemented on ships play a particularly pivotal role in the field of maritime transportation.

On the other hand, the EEOI and CII are operational measures, and their calculation rates are 52% and 40%, respectively. Therefore, studies that focus on these indicators are relatively more inclined to involve calculations. Given that the SEEMP is an operational mechanism, the calculation was performed in only 1 of 47 studies.

The article has used Energy Efficient Operation of Ships applications in the implementation of the SEEMP. The yearly distribution and the number of calculated indicators, which are the CII, EEDI, EEOI, EEXI, and SEEMP, are depicted in Figure 10.

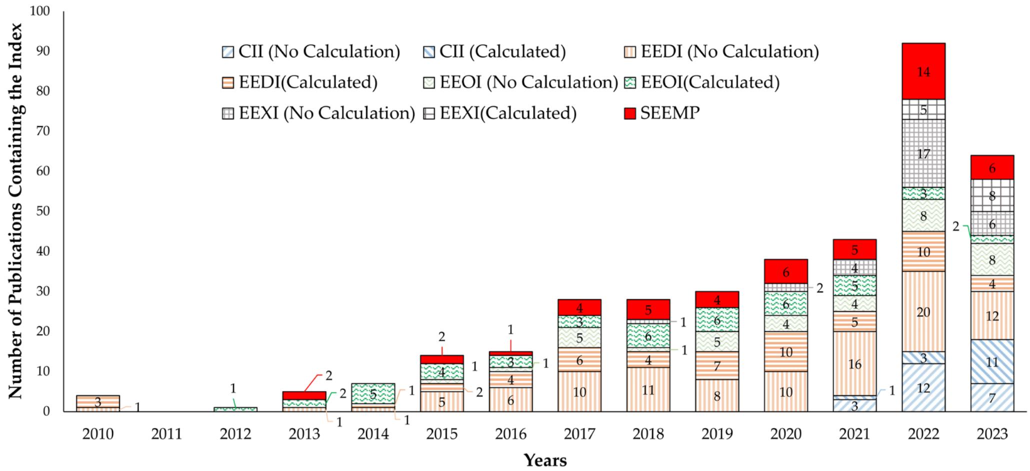

Figure 10. Yearly distribution of the metrics.

5. Discussion

As a discussion of the study, many different countries have contributed energy efficiency indicators in the maritime transportation literature. It has been observed that China, the Republic of Korea, Türkiye, and Norway are pioneer countries regarding examining these indicators. These outcomes are consistent with the IMO's perspective on maritime transportation-related countries [54]. Significantly, China, the Republic of Korea, and Japan are prominent shipbuilding nations with close ties to the design indexes [55]. Türkiye, a nation of significant importance in the field of ship scrapping and repair, is strategically located in proximity to maritime straits [56].

The inclusion of the Mediterranean Sea as an Emission Control Area (ECA) is also an efficient indicator of a country's strategic location. Conversely, Norway, situated in the Baltic Sea, has already been designated an ECA. Norway is also a significant maritime transportation hub involving various activities. It is noteworthy that all these countries possess well-established maritime research centers, which are instrumental in conducting analyses and shaping the energy efficiency agenda for the industry.

EEDI has emerged as the most extensively examined metric, accounting for 42.55% of the total research, followed by the EEOI at 22.49%. This significant focus on the EEDI indicates its pivotal role in shaping maritime regulations and fostering advancements in vessel design to enhance energy efficiency after the introduction date. Given the respective introduction years of these metrics, it is natural that the volume of studies about them surpasses that of other metrics.

Furthermore, the EEXI and the CII have experienced a notable increase over the past three years, presently recorded at 20.01% and 18.59%, respectively. This upward trajectory underscores the growing recognition of these metrics as essential tools for assessing and improving the environmental performance of existing vessels. The increasing literature surrounding the EEXI and CII highlights the industry's response to the emerging regulatory frameworks. It also emphasizes the urgent need for sustainable maritime practices. This focus ultimately contributes to the global efforts in mitigating climate change.

The EEDI, being the pioneering indicator among the specified ones, has consistently been investigated in studies throughout the period spanning from 2010 to 2023. Longva et al. [57] highlighted that the implementation of the EEDI in marine vessels will represent a crucial strategy for addressing and mitigating the GHG emissions within the maritime industry. The installation of energy-saving devices, the utilization of potential renewable and alternative energy sources instead of conventional ones, and the optimization of hull design, routing, and trim constitute fundamental measures for reducing the emissions from marine vessels and performing the necessity of the EEDI.

The primary parameters of the EEDI encompass the total emission quantity, reference speed, and the capacity of the ship. Holmegaard Kristensen [58] has described that the recently developed EEDI value can be lowered by up to 20% for a ship by adopting a well-selected engine, optimizing the hull design, and expanding the vessel's size without reducing the ship's speed. Polakis et al. [59] depicted that among several types of vessels, LNG carriers equipped with dual-fuel diesel–electric propulsion systems consistently maintain their operations below the EEDI reference values when operating in the gas mode.

Despite both the SEEMP and EEDI being introduced in the same year, under the specified literature, the authors initially mentioned the SEEMP in 2013. Coraddu et al. [60] and Bocchetti et al. [61] have only stated the indicator of the SEEMP in the abstract and introduction sections, respectively. In addition to reducing emissions, the SEEMP has also a notable impact on lowering the operational expenditures that raise fleet or ship performance. Any calculation of additional information has not been given throughout the article headings. On the other hand, the SEEMP has established a notable presence in the literature endeavors from 2013 to 2023.

Since the EEOI was the first operational measure, it has found a place in the early studies in this field. Figari et al. [62] have underlined that the indicator of the EEOI provides mitigating carbon emissions and establishing a structured framework for the implementation of carbon levies on maritime vessels. Although substantial research efforts have been performed on the EEOI until 2019, the introduction of the CII has led to a decrease in studies about the EEOI. Kobayashi et al. [63] stated that the application of route optimization has provided superiority in lowering the EEOI for regulatory compliance purposes.

In addition to voyage optimization, Im et al. [15] underlined that the installation of a controllable pitch propeller system, speed optimization, the continuous monitoring of machinery systems, cleaning of the ship hull and propeller, the integration of waste heat recovery systems (WHRSs), and the utilization of alternative fuels are prior and pivotal measures to provide energy efficiency operation of ships within the scope of the EEOI.

The research on the CII which is introduced instead of the EEOI by maritime authorities has experienced exponential growth post-2021 in the literature. Law et al. [51] assessed eight distinct types of marine fuels in terms of decarbonization strategies. While conventional HFO fuel remains at grade E in terms of the CII rating, carbon capture and storage applications utilized in both natural gas and conventional fuels, bio-MeOH, biodiesel, natural gas–hydrogen, natural gas–ammonia, and natural gas–electricity have enabled marine vessels to remain at grade A.

Apart from the utilization of alternative fuels, Zincir [64] highlighted that the application of slow steaming enables ships to easily achieve grade A in terms of their CII rating without the need for additional alternative systems. Like the CII indicator, the EEXI has been comprehensively investigated in the past two years of the literature.

Díaz-Secades et al. [65] underlined that an optimized WHRS has reduced the fuel consumption of the main engine and lowers both the attained EEXI and CII considerably. In addition to the proven reliability and energy-saving capabilities of WHRSs on marine vessels, Bayraktar [66] also stated that the utilization of commercially available alternative marine fuels, such as LNG and methanol, in both main and auxiliary engines has enabled the vessels to surpass the reference values for the EEXI and CII.

All the mentioned indicators set by the IMO have been used for the design, construction, and operation of sustainable and green maritime transportation globally. However, the widespread use of traditional fuel and machinery systems in marine vessels makes the compliance with these indicators difficult. Conversely, the increased efforts in energy efficiency saving applications over the recent decades are expected to significantly contribute to complying with these indexes.

6. Conclusions

Energy efficiency saving applications and regulations in maritime transportation have the utmost significance in achieving the sustainable development goals because these applications directly contribute to SDG 7: Affordable Clean Energy and SDG 13: Climate Action. Extensive research has been performed to enhance energy efficiency saving rates and mitigate carbon emissions originating from marine vessels within the scope of the maritime industry. The inferences described below have been obtained considering the studies examined:

The main outcomes of the study can be provided as follows. EEDI has been introduced as a technical measure, and the increasing awareness of the EEDI has the potential to ease the utilization of energy-saving devices, alternative propulsion systems, and more in marine vessels. The usage of alternative fuels encompassing low-carbon fuels such as LNG, methanol, and carbon-neutral fuels such as hydrogen, ammonia, and nuclear have a great impact on complying with the CII boundaries.

Alternative propulsion systems such as diesel electricity and hybrid propulsion systems have been highlighted to comply with the EEXI reference value. Moreover, the utilization of energy-saving devices and the selection of optimized and improved propeller types create more thrust that has a significant effect on energy saving and the attained EEXI value. SHaPoLI and EPL applications on traditional marine vessels using conventional propulsion systems and fuels are potential solutions to meet the short-term targets, especially in the calculation of the attained EEXI.

Governmental organizations and maritime authorities should support the utilization of the energy efficiency indexes, and they may give some incentives to provide a rapid transition. All the proposed solutions facilitate the compliance with all the indexes, even if they do not directly affect the specified indexes in the phase of the progress of providing sustainable maritime transportation. On the other hand, certain limitations have been considered during the execution of this investigation as described below.

The study has several limitations that should be acknowledged. Studies from the WoS and Scopus databases have been scrutinized since most scientific journals related to the maritime industry are available in these databases. Only four energy efficiency measurements, i.e., the CII, EEDI, EEOI, and EEXI, have been considered because these indexes cover both operational and technical issues, and all these indices considerably encompass other indices.

Furthermore, it may not be methodologically sound to analyze and discuss these studies in light of the limited number of articles that exist that are related to alternative indices. Exclusively English-language papers have been considered and studies in other languages have been eliminated. Only articles, book chapters, and conference papers related to these indices have been analyzed as document types.

It is recommended that future studies consider integrating with other databases, such as Google Scholar and ProQuest. In addition, papers in languages other than English will be considered. A further avenue for future research could involve a comprehensive review and analysis of these indicators, exploring both their positive and negative aspects, to inform the development of more sophisticated research methodologies.

Apart from these limitations, research endeavors will continue the investigation of energy efficiency measures because throughout the past, approximately thirteen years, new indexes have been defined, or existing indexes have undergone revisions. Moreover, numerous scientists are still working on these indices and persist in their efforts with the numerous numbers of papers.

Especially when a significant number of studies have been conducted on other indexes such as the Annual Efficiency Ratio, Energy Efficiency per Service Hour, Individual Ship Performance Indicator, and Fuel Oil Reduction Strategy not mentioned in this study, future investigations can be undertaken to include these indices.

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Appendix A

Table A1. "One indicator" cluster.

No	Citation	Year	Aim	Contribution
001	[67]	2010	The model includes a computation method to calculate the newly named EEDI, which is being developed by the IMO.	The study contributed to the literature by altering a few design parameters; the EEDI can be reduced by around 20% without decreasing the vessel's speed.
002	[57]	2010	This article describes a method for determining a needed index level (IR) by assessing the cost feasibility of the possible lowering options.	Setting an IR or a profitability-based cap avoids rigid rules on specific actions, while emission reductions and progress toward global targets can justify the costs of new standards.
003	[62]	2012	To explain how to determine the overall fuel consumption of a ship based on displacement and speed as random variables to assess the EEOI.	Providing accurate predictions via the Monte Carlo Simulation.
004	[68]	2013	To create a descriptive model between the EEOI and service conditions or environmental elements.	The study described operational strategies for improving energy efficiency.
005	[69]	2013	The study focuses on the idea of the EEOI which was created to help shipowners determine the emissions from operating ships and offer suggestions for reducing those emissions.	The study contributed to the literature that operational techniques, such as using different fuel types for different users, depending on the length of the voyage, can increase energy efficiency.
006	[70]	2013	To better understand the strategy for short sea shipping development in Croatia, and conduct SWOT analysis.	The analysis demonstrated that if the importance of policymaking focuses on the broader aspects of society, the economy, and environment in addition to the incorporation of external expenses, strengths, and opportunities, it will substantially reduce the impact of weaknesses and dangers.
007	[61]	2013	The study aimed to propose efficient fuel consumption for ships under the SEEMP.	The study contributed to the literature by proposing multiple linear regression analysis.
008	[71]	2014	The study aimed to explore the alternative marine fuels effects on the EEOI.	The study employed alternative marine fuel trade-offs regarding the EEOI.
009	[72]	2014	To establish a relationship between the vessel's displacement, GT, operating speed, and main and auxiliary power based on its dimensions, age, and building of ships.	Main and auxiliary powers are frequently selected as excessively large.
010	[43]	2014	To evaluate the performance of wave-devouring hydrofoil applications.	Employing energy efficiency and the reduction in the EEDI.

Table A1. *Cont.*

No	Citation	Year	Aim	Contribution
011	[73]	2014	To make recommendations for how to reduce operational emissions.	Comparative cost-to-quality graphs show the results for the performance metric EEOI and the mean price of obtaining them, highlighting the feasibility of the researched solutions for reducing air emissions.
012	[45]	2014	To calculate the effects of slow steaming in liner shipping and investigate the link between trip speed and CO_2 emissions.	Slow steaming is excellent for lowering CO_2 emissions; however, it is not necessarily helpful for lowering the operational expenses.
013	[74]	2014	To estimate the EEOI value before a cruise.	The EEOI has the impact of onboard measures on the journey energy efficiency.
014	[75]	2014	To suggest a dependable and effective strategy for predicting propelling performance.	It was determined from the outcomes that the suggested strategy may, when combined with ESDs' performance-improving effects, translate the model-scale findings to full-scale ones. It incorporates ESDs, unlike the current approaches, and uses a fraction of the computer power and time of full-scale CFD computations.
015	[76]	2015	The authors aimed to present the optimum design project SHOPERA.	The study introduced SHOPERA which provides guidelines for the optimal design of ships.
016	[41]	2015	The study targeted to investigate the ship's performance under various weather conditions.	Evaluating ship performance by collecting data from 20,000 DWT bulk carriers.
017	[10]	2015	The authors aimed to estimate the carbon emissions from bulk carrier fleets.	The authors preferred that the EEDI cannot help to reduce carbon emissions.
018	[77]	2015	To calculate real-time EEOI to provide optimal ship operation.	Calculating the real-time EEOI on board.
019	[78]	2015	To take environmental concerns into account when designing energy efficiency monitoring and control system.	Designing a system that is sensitive to environmental issues by providing energy efficiency.
020	[79]	2015	The study aimed to test the Ro-Pax and passenger ship EEDI calculation on Greece's inland water.	Large-sized Ro-Pax vessels had a high negative association between EEDI values and gross tonnage.
021	[80]	2015	The authors aimed to calculate the EEOI of the laden voyage of a tanker ship.	Finding an optimum EEOI value on a tanker ship.
022	[81]	2015	The study aimed to suggest credible and efficient wake prediction techniques for full-scale marine vessels.	The study proposed an efficient and reliable prediction method for ships.

Table A1. *Cont.*

No	Citation	Year	Aim	Contribution
023	[82]	2015	To analyze LNG carrier powering possibilities for the future while taking EEDI into account.	This article suggested techniques to incorporate methane slip emissions into the present EEDI calculations and analyzes the changes to the EEDI baseline values for LNG carriers.
024	[63]	2015	To propose a novel weather-routing optimization technology in this study that focuses on minimizing fuel usage and EEOI during travel.	The function in this study is the EEIO during a journey. Additionally, the transpacific route was selected for this study because it is one of the busiest marine routes.
025	[83]	2015	The authors aimed to propose a new method for calculating the EEOI.	The study contributed to the literature for exploring the real-time Energy Efficiency Operating Index.
026	[84]	2016	To calculate the EEOI for one of China's shipping companies.	Factors that affect the EEOI were identified, and suggestions were made for the shipping industry.
027	[85]	2016	The study aimed to select the best possible waste heat recovery system (WHRS) for a marine diesel engine.	Exergy analysis was employed for choosing the optimal WHRS.
028	[36]	2016	The study aimed to prioritize the ship's operational efficiency measures.	Revealing and prioritizing the operational efficiency measures.
029	[86]	2016	To calculate the EEDI and weather calculations for general cargo vessels.	Calculating the EEDI for general cargo vessels.
030	[87]	2016	To reduce the EEDI by calculating the propeller–hull performance during the ship optimization process.	Employing the CFD approach for reducing the EEDI in propeller–hull performance.
031	[88]	2016	To analyze the EEOI value on a well-predicted voyage.	Revealing the effects of early berthing prospects on the EEOI.
032	[89]	2016	The study aimed to investigate the wave effects on ship speed.	The study presented a methodology for exploring the wave effects of container ships.
033	[90]	2016	The study aimed to monitor EEDI with software.	This study contributed to the literature by suggesting software for ship energy efficiency. The suggested software is a useful tool for managing inventory and ship energy.
034	[91]	2016	To examine the interactions between the stakeholders in the Chinese shipbuilding sector and highlight the implementation's drivers and obstacles.	It is concluded that the EEDI has significant effects on not only China but also all other nations that have a shipbuilding sector. It may even lead to another industry relocation in the future.

Table A1. *Cont.*

No	Citation	Year	Aim	Contribution
035	[92]	2016	To present and anticipate future research directions in regard to the broad application prospects of sail-assisted ships. It describes the use of sail-assisted technology in the ship industry.	The study estimated that a new age in sailing science and technology will begin with the development of the sail-assisted ship, which can conserve energy and minimize pollution.
036	[93]	2016	The project's goal was to create the methods, tools, and guidelines necessary to address these issues and promote safe and environmentally friendly transport.	The study built a comparison and validation database that covers seakeeping and wave maneuvering in various environmental circumstances and water depths, with model tests.
037	[94]	2016	To provide a parametric design and optimization of container ships.	The study identified the optimal design that can be useful for the container shipping industry.
038	[95]	2017	The study targeted to find an alternative to provide energy efficiency for RO-RO ships.	The study employed real data for eight ships under new hull coating technologies.
039	[96]	2017	To explore the solar energy effects on the EEDI.	The study proved that solar energy is one of the pathways for meeting GHG emissions.
040	[18]	2017	To calculate the EEOI for a ship.	One of the important studies to calculate the EEOI on a 250,000 DWT tanker ship.
041	[97]	2017	To analyze the energy efficiency model in Artic navigation.	The study offered recommendations for enhancing the energy efficiency of Arctic navigation.
042	[49]	2017	To assess 5066 voyages made between 44 countries between 2013 and 2015 by 483 Very Large Crude Carriers (VLCCs) and determine the potential fuel savings.	The outcomes demonstrated the significant reductions in fuel expenditures and emissions, which are crucial for policymaking and the improvement of trip management in shipping businesses.
043	[98]	2017	To evaluate the EEDI and green technologies in shipping in terms of sustainable growth.	The study contributed to the literature by emphasizing that EEDI is not the representation of the overall vessel's energy efficiency. It should be monitored and lowered continuously in the future.
044	[48]	2017	To address the issues and promote safe and environmentally friendly shipping.	The main areas of focus are the greater resistance and drift forces at zero and moderate onward velocity, propulsion and rudder force tests in waves, and the evaluation of ship agility in waves compared to calm water circumstances.
045	[99]	2017	To examine the possible EEDI and CO_2 decrease for 405 Turkish-registered vessels.	It can be inferred from the estimates and discussions above that the Turkish Fleet's shift to new ships with EEDI designs will have a minimal impact.

Table A1. *Cont.*

No	Citation	Year	Aim	Contribution
046	[100]	2017	The results of the author's Ph.D. research, which was continued in this paper, were revised and confirmed considering the information from a previously published paper.	The study contributed to the literature in that this study resulted in one of the first attempts ever undertaken to create an EEDI baseline for various kinds of self-propelled inland ships.
047	[101]	2017	ESDs have been widely adopted as one of the countermeasures to the EEDI's CO_2 reduction requirement. The authors created a "Neighbour Duct" as one ESD, which was a vertical-long-oval stern duct.	As a result, it was discovered that Neighbour Duct may reduce CO_2 without altering the propeller or its design.
048	[102]	2018	The authors aimed to address the effects of ship size in large container ships.	The study inferred the formulation of the EEDI on large-size container ships based on DWT capacity and TEU.
049	[103]	2018	To create a new energy efficiency index for ships.	The study introduced energy efficiency and environmental eligibility for evaluating the environmental impact of ships.
050	[104]	2018	The study aimed to explore the potential fuels and set ups of future EEDI requirements.	The study revealed the EEDI adaptation under the whole possible situations of ships.
051	[105]	2018	To create an optimum navigation system for the Finnish winter.	Employing real-life data for creating route navigation.
052	[106]	2018	To reveal the EEOI is one of the most powerful indexes in maritime transportation.	Calculating the EEOI under different propulsion power.
053	[107]	2018	To investigate the current requirements of the EEDI on RoPax and container vessels.	The study contributed to the literature that presented that new models may enable more efficient, economical, and environmentally friendly designs for ships.
054	[108]	2018	To ascertain the sort of fatigue degradation of the carbon fiber reinforced plastic (CFRP) overlay-stimulated connection between I-core-type steel sandwich panels.	The study made the contribution that the use of composite overlays resulted in an average 1.8-fold increase in fatigue life.
055	[109]	2018	To evaluate the benefits of applying the suggested EEOI technique concerning specialized vessels.	The study proposed a new methodology to define the performed transport work.
056	[110]	2018	To define the EEDI more practically, based on several example vessel operating locations.	The study emphasized that the IMO may use the suggested strategy to enhance the framework for energy efficiency regulations.

Table A1. *Cont.*

No	Citation	Year	Aim	Contribution
057	[111]	2018	To present a novel method for evaluating the energy efficiency of passenger ships with integrated power systems that operate in a round-the-clock fashion.	The study contributed to the literature by proving that ships equipped with integrated power systems and hybrid power systems are not only capable of being more energy efficient but are also more so than the fleet average.
058	[112]	2018	To calculate for varying loads and speeds using an alternative model based on the response surface methodology.	The study revealed that the behavior of the chosen engines or engines that are comparable to them can be predicted using the generated equations.
059	[113]	2018	To investigate the seasonal variations of the EEOI.	The study underlined that EEOI savings of up to 20% can be ensured by considering the seasonal variations.
060	[114]	2019	To assess the basis for the standardization of the maneuverability of ships.	Assessing the maneuverability actions of ships in waves.
061	[115]	2019	The goal of the study was to calculate the EEOI using computer applications.	Calculating the EEOI for 250,000 DWT tanker ships with mathematical programming.
062	[40]	2019	To resolve the vessel speed optimization under uncertainty.	The study considered the uncertainty in the ice zone to calculate the EEOI.
063	[47]	2019	To reveal the challenges of the decarbonization path.	The study revealed the difficulties and opportunities of the decarbonization process.
064	[116]	2019	To employ EEDI to achieve the IMO's 2050 target.	Calculating and monitoring the EEDI on a real dry bulk carrier.
065	[117]	2019	To reveal the effects of ocean waves on the EEOI.	Employing a real case study between Chesapeake and the Mediterranean.
066	[118]	2019	To more thoroughly and scientifically assess ship shapes' degree of energy efficiency.	The study offered that LCA might be utilized as an energy efficiency assessment technique.
067	[119]	2019	To analyze the impact of the exhaust gas recirculation system and in the turbocharger's cut out on the EEDI.	This paper evaluated and reviewed the performance and dynamic characteristics of a marine diesel engine using a combination system of EGR and TCOO.
068	[120]	2019	To find the ideal size of a ship's carbon capture system for reducing GHG emissions.	The study contributed to the literature by emphasizing, with collaborative management, the equivalent average carbon capture level rises by 11.9%.

Table A1. *Cont.*

No	Citation	Year	Aim	Contribution
069	[121]	2019	To demonstrate how the deteriorating main engine affects the safety of ship handling in bad weather.	Both the simulation model with the standard engine power and the one that reduced the engine power to match the EEDI requirement were evaluated in these studies, and active-duty shipmasters steered the test ships through the choppy waters.
070	[122]	2020	To assess the safety of dual-fuel engine operation.	The study contributed to the literature that engine–turbocharger matching and waste gate control are the fundamental parameters to provide smooth compressor operation during the transition modes of dual-fuel engines.
071	[123]	2020	The EEDI performance of thirty gas carriers was analyzed.	The utilization of thermochemical regenerators has provided carbon emission reduction.
072	[124]	2020	To highlight the importance of the revised EEDI for the general cargo vessels operating on the inland water of Bangladesh.	The amended EEDI ensures sustainability for the inland waters in Bangladesh.
073	[46]	2020	To evaluate LNG in terms of decarbonization strategies in the maritime sector.	The study emphasized that LNG as a marine fuel is a good option for mitigating GHGs, but its reduction rate is limited.
074	[50]	2020	To provide a viewpoint to decrease GHGs.	The authors created an idea for decreasing not only CO_2 but also GHG emissions.
075	[125]	2020	The study aimed to examine the operation effectiveness of the Finnish Swedish Winter Navigation System (FSWNS) using a discrete event simulation-based methodology in this research. Performance parameters include transport capacity, the frequency with which icebreaker (IB) support was utilized, and the IB waiting times.	Case studies show that the EEDI laws may lead to a considerable rise in both the number of instances of IB assistance and the cumulative IB waiting times unless the number of IBs is raised.
076	[126]	2020	To examine the CO_2 emissions from inland oil tankers in Bangladesh.	Proposals that are offered by the study were used to remodel the vessels while maintaining their speed and capacity.
077	[127]	2020	To introduce a brand-new approach to estimating the EEOI for specialty ships that consider the specifics of their exploitation.	The analysis findings might be applied to controlling these ships' energy efficiency.
078	[128]	2020	To create a typical high-speed displacement vessel with a thin hull to lower the EEDI.	The study contributed to the literature by proposing that the EEDI may be used as an index to measure the stern flap effectiveness.

Table A1. *Cont.*

No	Citation	Year	Aim	Contribution
079	[129]	2021	To utilize optimization algorithms and a newly developed model on ship hull form to increase energy savings.	The study verified that the total amount of ship hull resistance has been reduced to comply with the EEDI via the utilization of the developed model and optimization algorithms.
080	[130]	2021	To highlight the economic performances of their methods which are LNG, scrubbers, and low sulfur oil utilization.	The study contributed to the literature by emphasizing that LNG utilization has great superiority to complying with regulations regarding the fuel price or initial cost of equipment.
081	[131]	2021	To evaluate wing devices that convert wave power to thrust power.	Emphasizing that wings have a lower total amount of fuel consumption and costs and provide environmentally friendly operation.
082	[132]	2021	To find the optimum ship route for operation cost reduction, energy efficiency, and sustainability.	Emphasizing that time windows are the best way to reduce operation costs and calculate the EEOI.
083	[133]	2021	The utilization of WHRS installations was analyzed on the ferry operating between Tallinn and Helsinki.	The study emphasized that WHRS is not suitable for the ferry operating between Estonia and Finland considering the volatility of the business environment and initial cost.
084	[134]	2021	To evaluate the effectiveness of the air lubrication method on a flat for achieving energy savings on ships.	The proposed system has provided resistance reduction at different air flow rates.
085	[135]	2021	This study aimed to introduce an energy-saving device and Twisted Rudder with Wavy Configuration have been investigated in terms of ship resistance, self-propulsion, and maneuverability.	Proving that a wavy twisted rudder has excellent propulsion performance.
086	[39]	2021	Comparing the EEOI and fleet energy efficiency management indexes of five bulk carriers.	The study contributed to the literature with a novel indicator as a fleet energy efficiency management index.
087	[44]	2021	To explore the paradoxes of the new CII regulations of the IMO.	The authors explored the new rules of CII regulations.
088	[136]	2021	To compare diesel and dual-fuel-powered tugboat emissions.	Suggesting to the sector to use LNG or dual-powered tugboats.
089	[137]	2021	To avoid tripping the BOG compressors when the ME-GI engines trip and to avoid a decrease in the amount of re-liquefaction, this study's goal was to present a novel control approach using a newly built configuration.	The simulation's findings supported the good re-liquefaction performance of the proposal and demonstrated exceptional controllability without tripping the BOG compressors even in unusual settings.

Table A1. *Cont.*

No	Citation	Year	Aim	Contribution
090	[138]	2021	To examine the realistic possibilities accessible to ship owners to satisfy the EEDI standards and identify the more advantageous solution in terms of technicality and adaptability concerns.	The technique of waste heat recovery presented in this study combines steam and power turbine generators to produce 2799 kW while improving the EEDI.
091	[129]	2021	To use the hull surface deformation approach based on radial basis function interpolation to modify the hull form and skeg shape of a 3000-t inland twin-skeg oil tanker with an undetectable bulbous bow.	A ship with exceptional resistance performance is achieved by ensuring that both the displacement of the ship and the longitudinal position of the buoyancy center are contained within the parameters of constraints.
092	[139]	2022	The introduction of an integrated energy system in the maritime field is presented.	The study highlighted the key points of an integrated energy microgrid utilized in marine applications.
093	[51]	2022	To assess the utilization of alternative fuel against HFO and reveal their potential advantages.	The maritime industry has the potential to achieve decarbonization by adopting specified alternative fuels but the cargo density and travel distance affect which alternative fuel will come to the fore.
094	[140]	2022	To review the calculation methods for inland vessels.	The study contributed to the literature on the EEDI for inland vessels.
095	[141]	2022	To find the efficiency level of the LNG carriers' propulsion system.	The study contributed to the literature on optimum propeller selection for LNG ships.
096	[142]	2022	To benchmark trimaran hull designs with and without an axe-bow on the main hull, as well as one with a monohull of equivalent displacement.	The study contributed to the literature by emphasizing that the trimaran without the axe bow can reduce the resistance by 22.6%, and the trimaran with the axe bow can reduce it by 25%.
097	[143]	2022	To quantitatively assess the fuel oil consumption patterns in the container shipping industry to determine whether the International Maritime Organization's (IMO's) aim of lowering ship carbon emissions can be achieved.	The study emphasized that it is not possible to meet the IMO targets, according to a conservative estimate of carbon emissions derived from a quantitative analysis of technological advancements in the fuel economy of container boats.
098	[144]	2022	To investigate the effect of wind-assisted propulsion on the EEOI.	According to the findings, fuel use and consequently GHG emissions can be decreased by up to 40% on an operating basis regarding the EEOI and by 30% when shipbuilding is considered.

Table A1. *Cont.*

No	Citation	Year	Aim	Contribution
099	[145]	2023	To investigate the capacity of a carbon capture system at the level of concept design for lowering the CII value of the VLCC tanker.	The study provided foresight about the utilization of a carbon capture system on the vessel considering its lifetime and regulations.
100	[146]	2023	To evaluate the current technologies from 68 articles to reduce GHG emissions.	In the study, renewable energy, fuel cells, and LNG utilization are the lead technologies.
101	[147]	2023	To evaluate the effect of carbon capture technologies on maritime transportation to comply with regulations.	The study contributed to the literature by reviewing the technological possibilities to reduce carbon emissions.
102	[148]	2023	To conduct resistance comparison analysis on the bulk carrier considering the calculation methods and towing tests.	The employed method gave the best results in the calculation of ship resistance.
103	[149]	2023	To verify tank tests and sea trail operation.	The study compared the validation studies and among the validation studies, NMRI (VESTA) gave the best results.
104	[150]	2023	To improve a formula to predict resistance.	The developed formula gave very close results with smaller mean percentage errors during the validation process.
105	[151]	2023	To reveal the seafarer's positions and hurdles for implementing energy efficiency issues.	The authors shed light on the literature to pave the way for a more sustainable maritime industry.
106	[152]	2023	To analyze effective implementation measures on the carbon intensity of ships.	They applied CII ratings on different types of ships.
107	[153]	2023	To compare the EEDI level and the required EEDI level.	Comparing the required EEDI and EEDI levels in Nitrogen Emissions Control Areas.
108	[154]	2023	To evaluate the effects of the CII on the Northeast Passage.	The study explored whether the CII rating will encourage a bigger size of ships.
109	[155]	2023	To reveal the effects of the CII on vessels' operations.	Evaluating CII results for 1-year routes of four vessels.
110	[156]	2023	To explore the effects of carbon capture WHRSs on the EEDI.	This paper contributed to the literature by emphasizing that the carbon capture method would effectively meet the forthcoming regulations.

Table A2. "Two indicators" cluster.

No	Citation	Year	Aim	Contribution
001	[42]	2015	To find a solution for complying with different countries' carbon legislation.	According to the authors, EEDI encourages decision makers to order fresh construction at a slower design speed.
002	[157]	2015	To thoroughly go over fundamental ideas, rules, and potential technology choices for green ships	The study contributed to the literature by providing options for machinery which are especially crucial since they increase efficiency while also being very effective at reducing NO_X and SO_X emissions during operation.
003	[158]	2016	To compare the EEDI and EEOI for a crude oil tanker ship.	Employing and comparing the EEDI and EEOI for ships.
004	[159]	2017	To discuss energy efficiency policies.	The study contributed to the literature by suggesting measures and implementations to reduce carbon emissions.
005	[160]	2017	To reveal the wave period effects.	Employing an Open FOAM coding process to reveal the ship's regular wave effects.
006	[161]	2017	To assess the SEEMP if it is sufficient to be a management system.	The study emphasized that the SEEMP should be integrated into the current management systems or completed with the aspects that are lacking to gain the status of the management system since it does not meet the formal standards for management systems.
007	[162]	2017	To review carbon capture systems (CCSs).	The paper demonstrated the economic viability of CCS on ships and offers practical installation guidance.
008	[163]	2017	To investigate the impact of three different WHRS designs on the EEDI and EEOI.	Systems for recovering waste heat may lower the ship's EEDI reduction factor to 20% below the value of the reference line.
009	[164]	2018	To identify the operational strategies for energy efficiency in the maritime industry that faces obstacles.	Aiding the maritime sector to diminish energy efficiency measures.
010	[165]	2018	To determine the slow steaming effects of the EEDI and EEOI on RO-RO cargo vessels.	Providing and calculating EEDI and EEOI calculations for reducing GHG emissions.
011	[166]	2018	To create a framework for adaptation to low-carbon shipping technology.	Providing a rational basis to support the application of the SEEMP.
012	[167]	2018	To investigate Distributed Energy Resources (DER) to enhance the efficiency and stability of the cruise vessels' grid.	Emphasizing that DER configuration has the potential to adopt various power generation technologies like fuel cells or energy-saving devices on board.

Table A2. *Cont.*

No	Citation	Year	Aim	Contribution
013	[121]	2019	To evaluate the influence of the degraded main engine and assess the maneuvering capability of masters.	The utilization of small-scale engines on ships affects the ship handling but its effect rates fluctuate according to the ship type.
014	[37]	2019	To investigate the connection between GHG emissions and fleet size.	Studies revealed that slowing steaming, and the EEDI, EEOI was able to reduce GHG emissions.
015	[168]	2019	To assess the solutions to the problems that lead to the primary diesel engine's exhaust gas turbine's functioning instability.	Providing the ease of selection of exhaust gas turbines.
016	[15]	2019	To propose an assessment method to determine the degree to which a ship fulfills its energy efficiency goal.	Providing an evaluation that the government and shipping businesses may find this approach helpful in determining how energy-efficient ship operations are.
017	[169]	2019	To optimize shipping operations to reduce the EEOI through a case study.	The proposed methodology can be useful to reduce operational emissions.
018	[170]	2019	To evaluate the implementation of Distributed Energy Resources on the grid of a cruise vessel	DER configuration has the potential to adopt various power generation technologies like fuel cells or energy-saving devices on board.
019	[171]	2019	The extra resistance and movements of a KCS (KRISO Container Ship) with a rudder were calculated using the commercial CFD program STAR-CCM+.	Five regular head waves with wavelengths ranging from short to long were taken into consideration in this investigation.
020	[172]	2020	To analyze the EEDI performance of the passenger/ro-ro ship.	The study emphasized that the passenger/ro-ro ship does not have an adequate performance to meet the EEDI reference value; therefore, energy efficiency measures such as alternative fuel utilization, hull and propeller optimization, and more should be implemented.
021	[173]	2020	To achieve EEDI compliance, education technologies on carbon emission were investigated from economic and environmental perspectives.	Emphasizing that the utilization of natural gas, treatment equipment, and ship speed reduction on the container ship are quite valuable options to provide energy efficiency savings.
022	[174]	2020	To reveal factors that affect the EEOI.	The study emphasized that an increased operational speed does not affect the EEOI.

Table A2. *Cont.*

No	Citation	Year	Aim	Contribution
023	[175]	2020	The study aimed to explore the effects of electricity consumers' general energy efficiency.	Approaching electricity consumers on the EEOI indicator.
024	[176]	2021	To specify the fundamental parameters related to the energy efficiency of ships highlighted by the IMO.	The study described the EEDI and EEOI as the fundamentals related to energy efficiency, but their extent should be developed to eliminate deficiency and uncertainty.
025	[177]	2021	To build the model, which was then integrated into the shipping sector to evaluate GHG measures.	The study contributed to the literature that zero-emission fuel should be utilized to achieve the 2050 target because the current measures are not adequate to comply with the upcoming regulations.
026	[178]	2021	To assess the carbon capture and storage system effect on the EEDI estimation of the ship.	The utilization of the carbon capture and storage (CCS) system on the ship has met the required EEDI reference value.
027	[179]	2021	To assess the performance of bilge keel appendages on wind-assisted ships.	The sailing efficiency of the ship was improved.
028	[180]	2021	To analyze the impact of seawater alkalinity, pH levels, and seawater flow rate on scrubber efficiency.	The enhancement in scrubber efficiency was attributed to the heightened seawater flow rate and increased alkalinity levels.
029	[181]	2021	To evaluate the maneuverability in adverse conditions while taking the requirements and revisions of the EEDI into consideration.	To achieve minimal propulsion power regulation crucial design criteria meant to guarantee safe navigation—propellers with larger light running margins are more desirable.
030	[182]	2021	To evaluate a ship's emission impact when employing cold ironing technology while at berth by optimizing the auxiliary engine operating profile and allowing regeneration into the port infrastructure.	The study proposed a cold-ironing power configuration. The results demonstrated excellent aggressiveness and precision that may be used for prolonged periods of ship operation while berthed.
031	[183]	2021	To describe the speed reduction effect on the EEDI and EEOI.	Speed reduction provided superiority in meeting the current and future IMO requirements.
032	[184]	2022	To improve ship energy efficiency with the utilization of various Pre-Swirl Duct models.	The study contributed to the literature that up to around 3% energy efficiency saving has been provided by the Pre-Swirl Duct.
033	[185]	2022	To evaluate speed and power reduction applications on bulk carriers to comply with existing and upcoming regulations.	Speed and power reductions are the potential resolution methods to comply with regulations.

Table A2. *Cont.*

No	Citation	Year	Aim	Contribution
034	[186]	2022	To review the stern hydrodynamic ESD effect.	Considering model tests and sea trails, ESDs provide energy savings ranging from 2% to 14%.
035	[187]	2022	To create an agent simulator to describe the effect of IMO requirements on maritime shipping	The authors developed a method to assist in the implementation of the IMO regulations and policy.
036	[188]	2022	To test the newly updated ITTC procedure.	Satisfactory results on the speed and power have been acquired by using the newly updated ITTC procedure
037	[189]	2022	To analyze the satisfaction of the reference value of the CII.	In addition to LNG, shore power connection and SOFCs constitute a reliable technological answer for upcoming regulations and environmentally friendly operations.
038	[190]	2022	To find correct EEDI baselines for the inland ships of Bangladesh considering only corrected ship data.	The EEDI baseline for inland ships should be region specific, as the EEDI baseline applied to ocean-going vessels is not suitable for inland ships.
039	[191]	2023	To show the speed reduction effect on the EEXI, CII, and CII ratings for container ships.	Optimized speed reduction has provided benefits from environmental, energy efficiency, and economic views for container ships.
040	[192]	2023	To consider whether different routes' operational efficiency optimization has been used as a short-term plan on existing ships.	Speed reduction has provided benefits in the stage of meeting carbon emission requirements.
041	[193]	2023	To create a nonlinear mixed-integer programming MIP model and propose a tailored exact algorithm to increase the energy efficiency level of each ship.	The study contributed to the literature by introducing a nonlinear MIP model. The operation cost and the average EEOI value have been decreased thanks to the model.
042	[194]	2023	To evaluate the carbon capture and storage applications for a ship.	The utilization of carbon capture and storage applications decreased CO_2 emissions considerably, and it is also quite economic with technological readiness compared to electrically propelled ship and hydrogen-fueled ships.
043	[195]	2023	To analyze the alternative scenarios of ship power systems.	Employing biofuels and renewable energy for ship power systems.
044	[65]	2023	To enhance WHRS in marine engines.	Investigating and presenting the best optimal WHRS in marine engines.

Table A2. *Cont.*

No	Citation	Year	Aim	Contribution
045	[196]	2023	To examine the economic, environmental, and forthcoming regulatory requirements for converting ship diesel engines to methanol.	The study contributed to the literature by examining several different factors for converting diesel engines to methanol fuel.
046	[197]	2023	To check the LNG dual-fuel engines for the present and the future.	The study added to the body of knowledge assessing the potential benefits of solid oxide fuel cells and water heat recovery systems used as auxiliary units with dual fuel engines that operate in primary fuel modes.
047	[66]	2023	To investigate alternative marine-fueled diesel engines and WHRS for preparing the carbon tax and forthcoming regulations.	The study filled the gap in the literature by applying alternative fuels and WHRS by considering forthcoming regulations and carbon taxes.

Table A3. "More than three indicators" cluster.

No	Citation	Year	Aim	Contribution
001	[198]	2017	The study aimed to create a framework for energy efficiency measures.	The study contributed to the literature by introducing Maritime Energy Specifications for keeping up with the new regulatory requirements.
002	[199]	2018	The study aimed to review energy efficiency improvement strategies for autonomous ships.	The study suggested employing a harmony of energy efficiency measures.
003	[200]	2018	To develop an energy efficiency assessment model.	The study presented a model to the literature for creating the architecture and road plan for the information system infrastructure, create the tools for the vessel's energy management system, and assess how this model influences vessel valuation by resulting in energy savings.
004	[201]	2019	To address the utilization of LNG as a clean fuel for ships, as well as operational and technical strategies for shipping that use less energy.	The chapter concluded with an evaluation of the difficulties in reducing emissions from the maritime sector after examining the effects of these rules.
005	[202]	2020	To provide information about energy efficiency indexes and describing applications to comply with these indexes	The study revealed the impact of potential applications on the indexes.

Table A3. *Cont.*

No	Citation	Year	Aim	Contribution
006	[38]	2020	To assess lower EEDI and EEOI values by the utilization of an Optimum Tracking-Based Control Scheme on the shaft generator.	The study emphasized that the developed strategies are quite beneficial to achieving the minimum emissions point.
007	[14]	2020	To investigate the SEEMP in terms of operational level considering the crew performance.	Operating procedures, competing goals, and stakeholder participation are the essential elements that need to be considered to improve the SEEMP.
008	[203]	2020	To reveal the potential actions for catching 2050 targets.	The study reviewed the potential actions for 2050 targets.
009	[182]	2021	To show the emission advantage of the Bi-Directional Power Flow Control Strategy utilized in Cold-Ironing Power Systems.	The Cold-Ironing Power Systems served with the control strategy are especially suitable for ships which have a high-power demand at berth.
010	[204]	2021	To determine uncertain factors on the amount of fuel consumption for ocean-going vessels.	The effect of weather conditions and the interactive relationship between the parameters investigated have been disclosed for the EEOI, and 550 tons corresponding to 27.5 fuel consumption savings have been provided.
011	[205]	2021	To evaluate energy-saving applications under the Floating Storage Regasification Unit (FSRU).	The study underlined that WHRSs, carbon capture and storage systems, and the utilization of low-carbon or carbon-neutral fuels are good solutions to meet the regulations.
012	[206]	2021	To ascertain how well-informed seafarers are on energy-saving techniques.	The study contributed to the literature examining energy efficiency measures in ships and companies.
013	[207]	2022	To explain how the exhaust gas boiler's temperature and flow rate affect the marine exhaust gas boiler's heat transfer coefficient.	The optimal temperature at each velocity was determined to achieve the best heat transfer coefficient because the heat transfer coefficient starts to decrease after a certain temperature increase.
014	[208]	2022	To predict speed and power using specified parameters for the oil tanker.	The parameters affecting power and speed were determined. The determined parameters were utilized in various regression models to predict power and speed. Regression Model.
015	[209]	2022	To evaluate whether GHG emissions sourced from mobile offshore units should be minimized and covered with regulations.	The study highlighted that GHG emissions sourced from mobile offshore units are quite critical to providing sustainability in the maritime sector. The fact that the MOU operator tends to reduce GHGs easier makes the implementation of this process easier.

Table A3. *Cont.*

No	Citation	Year	Aim	Contribution
016	[210]	2022	To investigate the ESD effect.	The formation of vortex and drag is minimized with suitable ESD utilization.
017	[211]	2022	To evaluate the application of the Internet of Things (IoT) for Bangladesh's maritime sector to comply with regulations and eliminate GHG gradually.	Showing how the IoT and augmented intelligence applications performed in the shipping industry.
018	[212]	2022	To present measures for short, medium, and long-term targets in the maritime sector.	The study emphasized that, to achieve the 2050 targets, clean fuel should be utilized, but these types of fuels should be affordable for the implementation.
019	[213]	2022	To highlight the application of engine power limitations and innovative technologies on the tanker to meet the IMO requirements.	The utilization of engine power limitation and specified innovative technology have met the EEDI requirements substantially.
020	[214]	2022	To provide decarbonization in the maritime industry.	The study revealed that specified shore power connection eliminates emissions from the ship at berth and this system provides advantages in terms of the CII index.
021	[215]	2022	To evaluate the commitment of Northern European seaports to monitoring the emissions of pollutants originating from cruise ships within their ports.	The study emphasized that the seaports of Northern Europe have committed to monitoring emissions originating from cruise ships, but innovative applications performed on the ports are quite capital and cost intensive.
022	[216]	2022	To investigate (MARPOL) Annex VI especially considering EEDI and SEEMP.	The study underlined that developing countries should be supported by technical awareness and financial support to achieve decarbonization.
023	[217]	2022	To investigate 22 mitigation measures in terms of the marginal abatement costs and GHG abatement potentials.	The study emphasized that the most implemented measures have negative cost impacts. On the other hand, the utilization of alternative fuel is rare, but they have big potential to reach the target.
024	[218]	2022	The study aimed to investigate the implementation of the EEXI in terms of energy, capacity, and CO_2 reduction cost.	The existing technologies provide a small reduction rate regarding the EEXI, and high-potential ones are immature and highly cost.

Table A3. *Cont.*

No	Citation	Year	Aim	Contribution
025	[219]	2022	The utilization of digital twins considering the performance of engine operations to perform green ship operation.	The study underlined that the clustering approach is one of the best ways to implement digital twins in ship operations.
026	[220]	2022	To evaluate ammonia as a marine fuel to achieve decarbonization on a bulk carrier for the maritime sector.	The study revealed that while ammonia has the potential for decarbonization, it is not cost-effective in the long term. Ammonia engines are useful for newly built ships.
027	[221]	2023	To investigate the energy efficiency of a ship considering onshore technical managers and onboard ship crews.	The study contributed to the literature by emphasizing that onshore technical managers and onboard ship crews are quite important for efficient ship operation.
028	[19]	2023	To reveal the effect of energy efficiency saving applications on different ship types in terms of upcoming regulations.	Both the utilization of low-carbon alternative fuels and power and speed reduction applications are very beneficial to comply with the regulations.
029	[64]	2023	To investigate slow steaming applications on marine vessels from environmental and economic aspects.	Both short- and long-term targets have been met by the utilization of slow steaming.
030	[222]	2023	To evaluate the effect of efficient training programs on the seafarers for the ship operation.	The study revealed that not all training programs are beneficial for seafarers to increase a ship's operation efficiency.
031	[223]	2023	The aim is to determine the best alternative system among the proposed ones to achieve decarbonization on marine vessels belonging to the Korean container fleet.	The utilization of LNG fuel retrofit is the best method to achieve decarbonization targets.
032	[224]	2023	To assess the EEXI of container vessels by using EPL.	To further cut down on GHG emissions, ships should run on low- or zero-carbon fuels in addition to EPL.
033	[225]	2023	To analyze ocean patrol vessel energy performance.	The study filled the gap in the literature emphasizing that a speed increase triggers significant amounts of carbon emissions, and electric propulsion systems are less efficient than traditional systems.
034	[226]	2023	To evaluate the attained EEXI values of Turkish-owned vessels.	The study provided an EPL application to meet the Phase 2 reference line for Turkish-owned vessels.
035	[227]	2023	To investigate the hull vane effect for high-speed craft in terms of drag, trim, and sinkage of the vessel.	The study provided advantages considering the aspects of drag, trim, and sinkage of the vessel and it decreased the index of the residuary resistance value up to 21%.

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