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Enhancement of Maritime Sector Decarbonization through the Integration of Fishing Vessels into IMO Energy Efficiency Measures

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Abstract: The escalating impact of anthropogenic activities on global climate patterns necessitates urgent measures to reduce emissions, with the maritime industry playing a pivotal role. This article aims to examine the adoption of International Maritime Organization energy efficiency measures for the often-overlooked fishing vessels and their contribution to the overall maritime decarbonization efforts. The article analyzes the attained technical efficiency indices of a case study large-scale fishing vessel and compares them with those of two cargo ships where IMO measures already apply. To support the proposal, a comprehensive analysis of the energy efficiency indices of eight large purse seine fishing vessels is also presented. The results show that large-scale fishing vessels of 400 GT and above could be subject to the IMO energy efficiency measures. The operational challenges, unique to the fishing sector, suggest that sector-specific considerations may be required to integrate the fishing fleet into the already existing IMO energy efficiency guidelines. Looking ahead, this article explores the benefits of aligning Regulation (EU) 2023/957 and IMO guidelines, as well as applying the IMO Carbon Intensity Indicator (CII) in assessing the operational environmental impact of fishing operations, emphasizing the importance of including these vessels in the current regulatory frameworks to promote decarbonization.

Keywords: industrial fisheries emissions; IMO energy efficiency measures; fuel use intensity; tuna purse seine fisheries; maritime decarbonization; EU MRV

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1. Introduction

The Sixth Assessment Report on climate change elaborated by the Intergovernmental Panel on Climate Change (IPCC) highlights the increase in global surface temperature of 1.09 °C from the pre-industrial era to the year 2020. Anthropogenic greenhouse gas emissions are largely responsible for this warming. It is noteworthy that CO_2 concentrations in the atmosphere reached 410 parts per million in 2019, which is higher than at any other time in the last two million years [1]. The transport sector as a whole emitted 8.26 Gt CO_2 in 2018, representing 25.93% of the total anthropogenic emissions in that year [2]. According to the Fourth Greenhouse Gas Study compiled by the International Maritime Organization (IMO), the maritime sector contributed with a 2.89% of the total (representing 12.78% of transport emissions) [3]. Although this may not seem to represent a large amount, maritime trade is expected to triple by 2050, with the associated pollutant emissions estimated to increase by 135% from the abovementioned 2018 levels [4,5].

At the moment, the IMO has established energy efficiency measures within the International Convention for the Prevention of Pollution from Ships (MARPOL) Annex VI, where the Ship Energy Efficiency Management Plan (SEEMP) applies to all vessels of 400 gross tonnage (GT) and above, including fishing vessels [6–8]. As of 2024, IMO mandatory energy efficiency measures for cargo vessels are essentially three: firstly, the Energy Efficiency Design Index (EEDI), a technical index used to assess the energy efficiency of new vessels, calculated during the construction phase and verified during sea trials [9]. When the IMO started to develop its energy efficiency strategies, it was decided that all newly built vessels should have an attained EEDI that was a certain percentage better than the already in-service ships. Due to the nature of the index, which uses the achieved EEDI of other ships to establish a reference line, it could not be calculated retroactively at the outset due to a lack of data. For this reason, the Estimated Index Value (EIV), a simplified formula for calculating the efficiency of existing ships, was created [10]. In Europe, Regulation (EU) 2015/757 adopted the EIV as an indicator, and to date, it is calculated for each ship and reported in its MRV CO_2 emissions report [11–13]. The second is also a technical measure, the EEDI equivalent but dedicated to already in-service vessels, the Energy Efficiency for Existing Ships (EEXI) index [14,15]. Both EEDI and EEXI regulations apply to ships of 400 GT and above that are engaged in international trade but not to the fishing sector.

In third place, the Carbon Intensity Index (CII) is the operational measure established by the IMO to monitor the annual CO_2 emissions of both new buildings and already in-service vessels [16,17]. This indicator is significant as it displays the actual quantity of CO_2 released into the atmosphere, based on real data for every specific vessel [18]. Additionally, it depicts the relationship between the ship's fuel consumption and its environmental impact, which could be interpreted as the societal value generated by the ship's carrying capacity and distance sailed. In this case, the CII is applied to ships of 5000 GT and above. To gather and later study the impact of the CII, data are collected by the International Maritime Organization in the Data Collection System (IMO DCS). This database is inspired by the European Monitoring, Reporting and Verification (MRV) system, which monitored approximately 11,800 ships that called port in Europe during 2021 [19,20]. Although there are no legislative precedents for the chosen threshold, the initial scope of the MRV monitoring plan was for ships of and above 5000 GT, but recent changes were made by the new Regulation (EU) 2023/957, amending Regulation (EU) 2015/757, and vessels of 400 GT and above will have to report their CO_2 emissions from January 2025 [12,21–23]. In addition, the EU has also added to the monitoring and control list methane and nitrous oxides [24]. Since the European Union has been at the forefront of decarbonizing the maritime industry, this amendment to the original EU Regulation may encourage a future change in IMO guidelines to make the CII reporting compulsory for ships of 400 GT and above, thus standardizing the coverage of their three energy efficiency measures [22,25–28].

Meanwhile, the IMO has several conventions that apply to the safety of fishing vessels, such as the 1995 STCW-F and the Torremolinos International Convention and its amendments of the 2012 Cape Town Agreement; the fishing sector does not have to comply with the IMO energy efficiency precepts, even if a part of the fleet exceeds the 400 and 5000 GT thresholds, with a propulsion power of up to 6000 kW, which could correspond to many small merchant or ferry vessels [29,30]. This sector of the maritime industry consumed 12.86 million tons of fuel during 2018 and emitted about 40.7 million tons of greenhouse gas emissions, which accounts for 4% of emissions of the maritime sector. This percentage is equivalent to the amount of GHGs emitted by the ferry-pax and cruise fleets [3,31,32]. While few fishing vessels are over 5000 GT, virtually only floating fish processors, the amount of fishing vessels of and over 400 GT is noticeable, particularly in the tuna fishing industry. The application of decarbonization regulations to this fleet would be helpful for the decarbonization of the maritime industry. Some advancements in the fishing industry have occurred in recent years, and countries like Spain implemented standards like the UNE 195006 Tuna for responsible fishing. For purse seine fishing vessels, it outlines the best practices towards the treatment of non-targeted species and decent labor of seafarers, but it does not include measures for reducing pollutant emissions [33].

Another remarkable similarity between the cruise and the fishing fleets is the distribution of energy demand on board. About half of the fuel burned on these vessels is used for their industrial purposes. While in cruise vessels this means hotel services for the passengers, in the fishing industry the burned fuel is mainly utilized to power the fishing gear. To a great extent, fuel consumption on board fishing fleets is determined by the type of gear used, with active gear such as trawls and dredges having the highest power demand due to the need for towing, the weight when full, and the drag force applied. If techniques like pulse trawling were used, electric power would be also needed for the fishing gear. In the case of passive gears like drift gillnets, the majority of the fuel consumption of the vessel is dedicated to sailing to and from the fishing grounds [34–36]. In general, fishing fleets that use passive gear tend to be less energy-intensive. In addition to active or passive gear usage, the role of fishing vessels in maritime decarbonization also varies with the depth of fishing. Deep-sea fishing, which uses bottom-contacting gears, harms vulnerable marine ecosystems and degrades blue carbon deposits, which store CO_2 emissions. Bottom trawling fishing impacts 4.9 million square kilometers of seafloor per year with penetration depths between 2.4 and 16.1 cm into the seabed, with the consequence of removing sediments that store organic carbon from CO_2 dissolution into the water and marine biodiversity deadfalls [37,38]. The avoidance of indirect CO_2 emissions produced by disturbing blue carbon deposits is acknowledged as an environmental measure [39]. Recognizing the necessity of safeguarding ecosystems from these harmful fishing practices, Europe enacted Council Regulation (EC) No. 734/2008 to protect vulnerable ecosystems from the impacts of bottom fishing gears [40].

To accurately measure CO_2 emissions from a fishing vessel and evaluate their impact, fishing effort is key. This is the reason why standard metrics used for merchant vessels are inadequate. The fishing fleet typically departs from port to the fishing grounds with no load, returning to port with their holds full so transport work always involves one trip in ballast condition. The current IMO framework considers ballast voyages as laden voyages, and fuel consumption in those conditions differ considerably [41]. As a result, energy efficiency calculations without any additional correction factor may be distorted, in comparison to other types of vessels [17,42]. Furthermore, the load is not predetermined as in the merchant sector since it depends on the amount and type of fish caught as well as the rate of bycatch, which vary by fishery. This can have negative consequences as certain fisheries require a larger effort in order to capture the same quantity of fish, resulting in a much lower catch per unit effort (CPUE). Moreover, regions like Europe have enforced a Landing Obligation since 2019 (EU Common Fisheries Policy, Art. 15), which mandates to retain on board the vessels' catches of species subject to catch limits but not directly targeted by the vessel. This policy results in less storage capacity for targeted species, elevating their CO_2 per kilogram rate. Another useful metric for quantifying the CO_2 emissions of the fishing fleet, in relation to societal benefits, is the Fuel Use Intensity (FUI) [43]. The FUI measures the fuel consumption of a specific vessel per kilogram of fish landed. This is essential for categorizing fisheries based on their emissions and promoting sustainable consumption habits [44]. Bastardie et al. analyzed the FUI of several Danish fisheries and found that not only the targeted species vary the FUI of the vessel but also the type of gear used. They also highlighted the limitations of their method, given the absence of any monitoring program that collects fuel consumption data from fishing vessels [45].

Regarding the adoption of energy efficiency indices to the fishing sector, Greer et al. presented a comprehensive study of CO_2 emissions in marine fisheries but obtained the FUI values inferring engine power, and did not obtain EEDI or CII values [46,47]. Similar indicators were analyzed by Byrne et al. in Icelandic fisheries. Three vessel types were studied in order to calculate average the Fuel Per Unit Catch (FPUC) and the CPUE. While the study provides very valuable insights, the authors used the category "above 200 GT" for the larger vessels, making it not possible to know whether they would be subject to the EEDI and EEXI. [48]; this also happened in [49]. In addition, Devi et al. studied the carbon emissions of small trawlers from north-west India, but their case vessels were not eligible for IMO measures due to their capacity, which is less than 400 GT, and the carbon emission factor utilized was not in line with the one established by the IMO (2.7 vs. 3.206 kg of CO_2 per kg of fuel, respectively) [50]. Koričan et al. looked into the different technical alternatives to improve the environmental impact of fishing trawlers but overlooked the necessity of an energy efficiency categorization [43]. Recently, in September 2023, the workshop titled "Challenges and opportunities for EU fisheries and aquaculture" emphasized the need to promote the presence of fishing vessels in IMO environmental policies. The workshop encouraged the installation of energy-monitoring devices in the fleet to report data to the IMO's database [51].

Based on the above literature review, the following research gaps have been identified:

- Although large fishing vessels may have similar size and power to some merchant ships, they are not subject to IMO energy efficiency measures.
- Previous literature has explored various energy efficiency indices for fishing vessels but has not proposed adopting the already established measures.
- To apply these indices correctly, it is necessary to develop specific correction factors for the fishing industry.

This paper proposes implementing the IMO energy efficiency measures in large fishing vessels to accelerate the decarbonization of the fishing sector. To demonstrate the benefits of implementing IMO measures to reduce CO_2 emissions, a comparison between a large-scale tuna fishing vessel and two cargo ships was made. Following this comparison, and using the same methodology, a comprehensive study of the energy efficiency indices of eight large purse seine tuna vessels was conducted.

2. Materials and Methods

Energy Efficiency Measures Applied to Large Fishing Vessels: Comparison with Merchant Ships

Improving energy efficiency in the fishing industry could aid decarbonization to a great extent. In this section, a comparison between two cargo vessels versus a large purse seine tuna fishing vessel is presented. This particular type of fishing vessel was selected because, according to the Tuna Consolidated List of Authorized Vessels (CLAV) database, 307 purse seine vessels from 499 to 4406 GT are licensed to fish tuna in the different RFMOs [29]. This type of vessel would be subject to comply with the energy efficiency indices EEDI and EEXI if IMO energy efficiency measures were applied to fishing vessels. Although there are other important fishing fleets in number, their size makes them not eligible for the IMO energy efficiency measures [52]. Carbon Intensity Indicator is not calculated as current regulations do not apply for vessels of this tonnage.

To illustrate the benefits of implementing IMO energy efficiency measures on fishing vessels, a case study comparison is provided. For that purpose, a large fishing vessel is compared to two merchant ships of similar size that already adopted IMO guidelines. In the first place, a ferry vessel that operates in a fixed route inside the EU space is chosen. The selection is made on the basis of length, gross tonnage and power of the vessel, looking for a case with similar characteristics to the selected fishing vessel which is to be compared. Secondly, a chemical/oil products tanker with similar size and power is chosen. In this case, the vessel is mainly used to distribute gasoline and diesel fuel between the various islands of an archipelago but without a fixed route. This adds interest to the comparison, since the variable routing of the tanker is similar to the way that fishing vessels operate, and reveals that some merchant ships are less powerful than many large fishing ships. For the fishing vessel, a large-scale purse seine tuna fishing vessel has been selected. As an example, the Spanish tuna fishing fleet has vessels sensitive to meet IMO energy efficiency indices which are between 52 and 116 m of length, with gross tonnages from 912 to 4406 GTs and engine power that starts at 1471 kW and can reach up to 5851 kW [53,54]. These features make this specific type of fishing vessel equivalent to the merchant fleet, in terms of emissions, and theoretically eligible for the IMO energy efficiency measures. In Table 1, particulars of each of the compared vessels are displayed.

Table 1 includes both propulsion and auxiliary power values since they are both taken into account in EEDI calculations. While the ferry vessel and the tuna fishing vessel have a total power, composed of propulsion and auxiliary engines, of around ten thousand kilowatts, the oil tanker only reaches a total of 4640 kW. This proves some fishing vessels are equivalent or larger than some merchant vessels. Although the power differs from the other two vessels, the oil tanker has been included in the study due to her similar size and variable routing. It is of special interest to remark that, in terms of auxiliary power, the studied fishing vessel has 3680 kW installed. This represents 2.2 and 3.1 times the power installed in the ferry and the oil tanker, respectively.

Table 1. Particulars of case study vessels, adapted from [11,55].

	Merchant Vessel 1	Merchant Vessel 2	Fishing Vessel
Type	Ferry	Oil tanker	Tuna fishing
Route	Fixed, crossing the strait of Gibraltar	Variable	Variable, several fishing grounds
Construction year	2009	2011	2004
Length (m)	101	113	116
Gross Tonnage (GT)	6146	5424	4406
Deadweight (tons)	850	7533	3630
Main engine power (kW)	9000	3440	6300
Specific fuel consumption of main engine (gFuel/kWh)	173.8	188.0	180.0
Auxiliary engine power (kW)	1680	1200	3680
Specific fuel consumption of aux. engine (gFuel/kWh)	215	215	215
Carbon emission factor (gCO_2/gFuel)	3.1144	3.1144	3.206
Fuel monitoring method	B [1]	B [1]	N/A [2]
EIV 2022 (gCO_2/t·nm)	38.90	27.08	N/A [2]

[1] Fuel monitoring method B: bunker fuel tank monitoring on board, in accordance with Regulation (EU) 2015/757, Annex 1 [12]. [2] Fishing vessels are not required to comply with Regulation (EU) 2015/757 and therefore do not report their fuel consumption nor calculate their EIV.

To establish a benchmark, energy efficiency data for the two cargo vessels during the year 2022 were retrieved from the European MRV system, specifically the Estimated Index Value (EIV), in grams of CO_2 released by the ship per ton of cargo and nautical mile sailed. This was necessary because the IMO DCS is a closed database [11,56]. During the 63rd meeting of the Marine Environment Protection Committee [MEPC(63)], the Estimated Index Value was created as a simplified formula of the EEDI to be applied to already in-service vessels [10]. Although the formula has some flaws, it resulted very helpful to calculate initial EEDI reference lines. Faber et al. analyzed the correlation between EIV and EEDI, concluding that EIV values were slightly higher than the attained EEDI [57]. In Europe, Regulation (EU) 2015/757 stipulates in articles 11(3) and 21(2) the legal obligation to publicly disclose the technical efficiency of the ship and still accepts the EIV index to this day [11,12]. Since the EIV value for the fishing vessel does not appear in the EMSA THETIS-MRV database, it will be calculated in the following lines using Equation (1) [10]:

$$Estimated\ Index\ Value = 3.1144 \cdot \frac{190 \cdot \sum_{i=1}^{NME} P_{MEi} + 215 \cdot P_{AE}}{Capacity \cdot V_{ref}} \quad (1)$$

where the value of 3.1144 represents the carbon emission factor, assuming all engines use heavy fuel oil, P_{MEi} is 75% of the total installed main power, P_{AE} the auxiliary power, and the values 190 and 215 are the assumed specific fuel consumption for main and auxiliary engines, respectively. The term V_{ref} is the service speed of the vessel.

On top of their power, purse seine tuna fishing vessels are equipped with a small support boat designed to assist with the net and, in this case study, powered by an engine of 956 kW. Support boats are usually highly powered due to the need to stay in place and hold the beginning of the net while the purse seine is encircling the tuna school. Moreover, five speedboats with approximately 100 kW each are utilized during fishing operations. These skiffs are key to help keeping the tuna inside the net while it is closing. While cargo vessels are equipped with fast rescue boats that could be comparable with the tuna fishing skiffs, these are intended for emergency use only, so the amount of fuel consumed during the life cycle of the vessel is negligible. Helicopters are frequently employed by the tuna fishing fleet in order to locate tuna schools, being popular maneuverable models like the

McDonnell Douglas MD 500 and the Robinson R22 and R44 [58–60]. The use of all support vehicles during fishing is important to consider due to the additional amount of fuel needed. Table 2 includes average consumption of accessory vehicles used for the case study tuna fishing vessel:

Table 2. Average consumption of tuna fishing vessel accessory vehicles.

Vehicle	Average Consumption (L/h)	Units on Board	Type of Fuel	Carbon Emission Factor (gCO_2/gFuel)
Support boat	125.8 [1]	1	Diesel	3.206
Skiff	32.0 [2]	5	Diesel	3.206
Helicopter	65.6 [3]	1	AvGas	3.048 [4]

[1] Caterpillar C32 fuel consumption at 50% average load. [2] Volvo-Penta D8 fuel consumption at 60% average load. [3] Average consumption of the helicopter was determined by averaging the fuel consumption of the MD500, R44 and R22 models. [4] Obtained from [61].

In order to obtain the attained Energy Efficiency Design Index of the three studied vessels, calculation as per IMO guidelines MEPC.364(79) is performed through Equation (2) and data from Tables 1 and 2:

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

where main engines' power, identified by P_{ME}, are measured at 75% of the rated installed power of each propulsion engine. And for the auxiliary engines, which provide the vessel with electric power, the MEPC.364(79) provides several calculation methods, depending on the propulsion power of the vessel and if it is classified as an LNG carrier. In this work, all vessels have a propulsion power of less of 10,000 kW, so P_{AE} is obtained by Equation (3):

$$P_{AE\ (\sum MCR_{ME(i)}<10{,}000\ kW)} = \left(0.05\cdot\left(\sum_{i=1}^{nME} MCR_{ME(i)} + \frac{\sum_{i=1}^{nPTI} P_{PTI(i)}}{0.75}\right)\right) \quad (3)$$

where the applicable power, P_{AE}, is 5% of the total propulsion power of the ship, MCR_{ME}, plus the total power of shaft motors, P_{PTI}, divided by 0.75. In the case study presented, none of the vessels are equipped with shaft motors.

Back to Equation (2), the term C_F is the CO_2 emission factor of main and auxiliary engines, (ME and AE, respectively). This is represented separately as each consumer could use a different type of fuel. In the general case of merchant vessels, and also in the two selected for study, the fuel used is heavy fuel oil (HFO), which has a carbon emission factor of 3.114. When applied to fishing vessels, the C_F factor would typically take a value of 3.206 ton of CO_2 per ton of fuel, as it has been reported that over 96% of the fishing industry uses diesel [3,62]. *SFC* represents the specific fuel consumption of the engine, measured in g/kWh and corrected according to the corresponding values of ISO 15550:2016, for standard reference conditions, and ISO 3046-1:2002 for the lower heating value of the fuel [63,64]. The term *Capacity* is related to the type of vessel. For tankers and other cargo carriers, the MEPC.364(79) considers deadweight when referring to capacity, whereas for passenger vessels, the reference is gross tonnage. The utilization of the internal volume, which is more relevant for assessing the space available for passengers, amenities, and safety features, was carried out due to the absence of pure cargo in passenger vessels, having only fuel, supplies and provisions on board [14,65]. For the calculation of the EEDI of the purse seine tuna fishing vessel, *Capacity* was calculated using the deadweight of the ship. Although other references use the gross tonnage [66,67], the utilization of the deadweight for the calculation was carried out because, in a sense, the holds of fishing vessels are designed to carry cargo and the energy efficiency of these vessels should be linked to the amount of biodiversity they can contain. Lastly, V_{ref} represents the average speed of a vessel under normal load and weather conditions, which is assumed to be the speed of the vessel at 75% MCR under the draught condition corresponding to the aforementioned *Capacity*. In addition, the average fuel consumption of each auxiliary vehicle, as shown in Table 2, is being multiplied by its carbon emission factor in order to obtain the amount of CO_2 produced by the support boat, the skiffs and the helicopter.

On top of the general terms, the EEDI formula contains six correction factors: f_j, f_i, f_c, f_l, f_w and f_m. These correspond to ship-specific design elements, technical limitation on capacity, cubic capacity, cargo-related gear, speed reduction and IA Super/IA ice-classed vessels, respectively. In this study, the correction factors most applicable to the purse seine tuna fishing vessel are the terms f_j and f_l, which pertain to the shape of the vessel and its cranes and cargo gear, respectively. First, the f_j correction factor is calculated using the formula applied to general cargo ships in Resolution MEPC.364(79):

$$f_j = \frac{0.174}{Fn_{\nabla}^{2.3} \cdot C_b^{0.3}} \tag{4}$$

where Fn is function of V_{ref} and the displacement of the vessel but limited to 0.6; and C_b is the block coefficient, estimated to be 0.525 for the majority of tuna fishing vessels. Although f_j has several ship categories, only "general cargo" and "others" are applicable to large fishing vessels, due to their characteristics. In this study, the "general cargo" type of calculation was chosen because of its specificity, as the equation takes into account block coefficient of the vessel, length and beam, while the "others" category assigns all ships a value of $f_j = 1$.

Craning devices are essential in their operations since several skiffs are deployed for support and the net has to be set and then hauled. The correction factor applicable due to the presence of cargo related gear is calculated by Equation (5):

$$f_l = 1 + \frac{\sum_{n=1}^{n} (0.0519 \cdot SWL \cdot Reach_n + 32.11)}{Capacity} \tag{5}$$

where SWL is the Safe Working Load of each crane, as specified by the manufacturer. The term *Reach* represents the maximum extension at which SWL can be applied. Deck equipment particulars are presented in Table 3.

Table 3. Types of cranes on board tuna fishing vessels, adapted from [68,69].

Crane Type	Units on Board	SWL (tons)	Reach (m)
Power block	1	30	25
Auxiliary boom #1	1	10	14
Auxiliary boom #2	1	3	12
Speed boats crane	4	4	10
Net stacker	1	0.5	10

Finally, the EEDI formula includes a correction factor, denoted as f_{eff}, that is applied to each innovative energy efficiency technology installed on board. The main energy efficiency technologies are summarized in the 2021 Guidance on treatment of innovative energy efficiency technologies for calculation and verification of the attained EEDI and EEXI (MEPC.1/Circ.896) and already treated in the scientific literature [70–74].

3. Results and Discussion

After calculation, attained EEDI values of the three studied vessels are displayed in Table 4. Although the suitable IMO correction factors were applied to the fishing vessel, its energy efficiency index was much higher compared to cargo vessels that were of similar size.

Table 4. Attained EIV and EEDI values of case study vessels.

	Ferry	Tanker	Fishing Vessel
Attained EIV ($gCO_2/t{\cdot}nm$)	38.90 *	27.08 *	56.68
Attained EEDI ($gCO_2/t{\cdot}nm$)	8.21	20.20	31.06

* Values obtained from the EMSA THETIS-MRV CO_2 emission report database [11].

The EIV calculation for the fishing vessel, which is a simplified version of the EEDI without any correction factors, yielded a value of 56.68 $gCO_2/t{\cdot}nm$, which significantly exceeds the EIV values of the compared cargo vessels. This is also because the EIV is a simplified formula that does not take any correction factor into account and considers the consumption of the main and auxiliary engines to be constant when not all engines have the same specifications.

However, the fishing vessel's attained EEDI is 3.78 times greater than the ferry vessel's and 1.54 times greater than the tanker's. The tuna fishing vessel under consideration presents the disadvantage of having a relatively low $Capacity$ while compared with the other two vessels, albeit with high propulsion power. The inclusion of the fuel consumption of auxiliary vehicles changes the EEDI value only minimally, as the majority of the ship's consumption takes place during the cruising phase. The application of the ship-specific design factor, quantified at 0.683, and the craning gear factor, quantified at 1.086, reduces the obtained value but still results in an attained EEDI value higher than the attained index of the other two merchant vessels.

Consequently, the results of the attained EIV and EEDI values for the three vessels indicate the need to include large-scale fishing vessels in the IMO energy efficiency regulations, while developing the appropriate correction factors. The inclusion of large fishing vessels of 400 GT and above in the IMO energy efficiency measures will contribute substantially to the decarbonization of the maritime industry.

3.1. EIV and EEXI of Large Fishing Vessels

Using the aforementioned methodology, this subsection will explore the attained EIV and EEXI values of eight other large purse seine tuna fishing vessels. The data were taken from Basurko et al.'s research due to the diversity of ships by power and year of construction, and all meeting the requirement of being over 400 GT to be included in the current IMO energy efficiency measures [75]. Parameters used for calculation are shown in Table 5:

Table 5. Particulars of large fishing purse seine vessels, adapted from [62].

	Vessel 1	Vessel 2	Vessel 3	Vessel 4	Vessel 5	Vessel 6	Vessel 7	Vessel 8
Construction year	2014	1983	2009	1991	1990	1976	2014	2014
Length (m)	88.6	52.3	87.0	75.6	105.0	76.7	78.0	91.1
Beam (m)	14.0	14.0	14.2	13.6	16.8	13.5	14.2	14.7
Draught (m)	6.70	4.95	6.51	6.62	7.19	6.01	6.30	6.95
Gross Tonnage (GT)	2755	912	2548	2101	4164	1897	2591	2863
Deadweight (tons)	2467	650	2358	1600	1905	1567	2182	2255
Main engine power (kW)	4564	1491	4474	2941	6083	2983	4543	5966
Specific fuel consumption Main Engine (gFuel/kWh) [1]	190	190	190	190	190	190	190	190
Auxiliary engine power (kW) [2]	3000	3000	3000	3000	3000	3000	3000	3000
Specific fuel consumption Aux. Engine (gFuel/kWh) [1]	215	215	215	215	215	215	215	215

[1] Specific fuel consumption is set at 190 and 215 gFuel/kWh for the main and auxiliary engines, respectively, as per MEPC.350(78) [76]. [2] In the absence of detailed auxiliary engine power data, an average of 3000 kW has been used.

Estimated Index Value of vessels was calculated directly applying the parameters shown in Table 5 into Equation (1). For the EEXI calculation, the f_j correction factor is obtained by using Equation (4) and the particulars of each vessel. In the absence of data, the correction factor applicable due to the presence of cargo related has been established as 1.086 for all vessels, taking the value obtained in the case study presented in Section 2. Table 6 presents the results of the f_j correction factor and both EIV and EEXI for each of the eight vessels analyzed.

Table 6. Attained EIV and EEDI values for large fishing purse seine vessels.

	Vessel 1	Vessel 2	Vessel 3	Vessel 4	Vessel 5	Vessel 6	Vessel 7	Vessel 8
Ship-specific design correction factor	0.504	0.367	0.498	0.467	0.593	0.451	0.472	0.527
Attained EIV ($gCO_2/t{\cdot}nm$)	71.05	117.29	73.02	79.18	107.11	81.35	78.95	91.17
Attained EEXI ($gCO_2/t{\cdot}nm$)	27.01	38.94	27.47	29.00	46.73	28.90	28.24	35.62

The attained EIV values are very high in comparison with merchant vessels. The obtained mean EIV of the eight vessels analyzed in Table 6 is 87.39 $gCO_2/t{\cdot}nm$, while the mean EEXI is 32.74 $gCO_2/t{\cdot}nm$. In comparison, the mean attained EIV and EEXI by vessels built between 2009 and 2016 is displayed in Table 7:

Table 7. Mean EIV and EEDI values for merchant vessels (2009–2016), adapted from [77].

	Bulk Carriers	Container Ships	Tankers	Gas Carriers	General Cargo	Average Merchant Vessels
Mean EIV ($gCO_2/t{\cdot}nm$)	5.17	17.06	8.41	16.50	13.59	12.15
Mean EEXI ($gCO_2/t{\cdot}nm$)	4.64	15.36	7.56	14.84	12.09	10.90

Although large purse seine tuna fishing vessels are favored by the use of correction factors due to the use of cargo-related gear and ship design, which is the reason why their EIV values are higher than EEXI, their technical energy efficiency index is higher than that of merchant vessels. This happens because their propulsion power is similar to many mid-size merchant vessels but generally have much more auxiliary power, due to the high demand for electricity to power fishing gear. Furthermore, the low deadweight values and lower reference speed contribute to attain very high EEXI values. When similar purse seine vessels are compared, the deadweight of the vessels plays a key role, as many of the other parameters are very similar between vessels. For instance, two similar-sized vessels (case study in Table 1 and vessel 5 in Table 5) attained EEXI values of 31.06 and 46.73, respectively. And the major difference was in deadweight (3630 vs. 1905 tons, respectively) and reference speed (16.99 vs. 18.13 knots, respectively). These differences may be partly due to the difference between its year of construction (2004 vs. 1990) and the evolution of shipbuilding technologies. In this sense, the vessels that can carry more weight will come out as winners, as they emit less CO_2 for the same amount of cargo.

3.2. Correction Factors Proposal

After the adaptation of merchant vessels' procedures to evaluate the technical energy efficiency of large-scale purse seine tuna fishing vessels, the results showed the necessity to observe the particulars of fishing vessels operations and to develop correction factors according to their requirements such as the following:

- Gear type: From a general standpoint, fishing equipment can be divided into passive and active gears. Depending on the type, fuel consumed on board is put to a specific purpose. In the case of passive gears, a significant portion of the fuel is used to sail to and from the fishing grounds and for finding fish. For this type of fishing, mitigation strategies like route optimization and slow steaming could mitigate the fuel consumption [78]. In the case of active gears like trawling, the majority of the fuel is consumed during fishing operations, due to the gear's need to be dragged or hoisted. Drag-force reduction should be applied either to the hull or the gear [35,79]. A correction factor tied to the type of gear used could help to normalize fuel consumptions within the fleet.

- Depth: In those types of fishing where the sea bottom is altered, a penalty corrective factor should be imposed. Those fishing vessels not only release CO_2 and other harmful gases from their machinery into the air but also damage the blue carbon deposits, where a large part of CO_2 is captured. When a blue carbon deposit is degraded, there is a high risk of releasing the contained CO_2 back into the atmosphere [80]. Although beam trawling techniques were partially substituted with electricity and pulse trawling, due to the higher fuel efficiency than traditional trawling methods and reduced destruction of the seabed, the technique itself has been deemed very controversial and banned in Europe since 2019 [81]. Therefore, pelagic and other demersal non-destructive methods should be preferred due to the lower amount of total pollution released [82].
- Catch and Fuel ratios: Two already established metrics, Catch Per Unit of Effort (CPUE), an indication of abundance in fisheries expressed in mass per time unit of fishing effort, and Fuel Use Intensity (FUI) expressed in liters per kilogram of catch, should be monitored for determining and comparing the energy efficiency of fishing vessels. Some vessels may have to spend more time in the fishing grounds than others due to the level of depletion of the targeted species, leading to a decrease in their CPUE. Watson et al. examined global CPUE from 1950 to 2006 and found that it decreased by half during that period [83]. This decline reflects a reduction in abundance and suggests that fishing vessels may need to increase their operational time in order to capture the same amount of fish. In some cases, catch methods of a particular species can also affect the CPUE. In the last decades, large-scale tuna fishing in the Indian Ocean has shifted its focus from free-swimming tuna schools to targeting fishing aggregated device (FAD) schools. Parker et al. analyzed the differences in fuel consumption between these two capture techniques and found that FAD fishing results in a higher fuel consumption per kilogram landed [84]. Meanwhile, other fishing vessels may be more energy-intensive due to the type of gear used, such as trawling, or due to the distance from port to the fishing grounds, which has been generally increased since 1950 [85]. The introduction of fishing-specific correction factors that consider the fishing effort and the fuel intensity of each specific type of fishing may help to classify fishing vessels' efficiency more appropriately.
- Use of other artificial means: Techniques like large-scale purse seine tuna fishing often involve a support vessel in order to encircle the net and later assure the stability of the mother vessel when lifting the net. Also, several speed boats are used to control the tuna school and prevent escape, and in some cases accompanied by a helicopter used to locate the tuna. All these auxiliary vehicles are needed for their regular fishing operations and have a fuel consumption, with their associated emissions, that should be included in energy efficiency calculations. This differs from merchant vessels where rescue boats are only started for regular maintenance and utilized in emergency situations, resulting in a minimal or greatly justified fuel consumption [14]. The use of artificial lights should be also considered as their electric consumption during fishing activities can be substantial.
- Refrigerant leaks: Conserving the catch during transit from the fishing grounds to port is a crucial aspect of modern fishing. Freezing systems are widely used in the fishing fleet, using refrigeration gases that could deplete the ozone layer and contribute to global warming. While R22 was traditionally used, it has been phased out by the Montreal Protocol [86]. Presently, CO_2 and ammonia are the primary refrigerants employed in freezing systems. These gases have very low Greenhouse Warming Potential (GWP) but should be taken into account as high refrigerant gas leakages from marine vessels usually occur due to the constant motion and vibrations [87].

Analyzing the specific characteristics of each fishery operation can provide a better understanding of the fleet's emissions. This may subsequently accelerate the decarbonization of the industry.

4. Future Application of the Carbon Intensity Indicator

In addition to the technical efficiency indices established by the IMO, the Carbon Intensity Indicator (CII) calculates the ratio of emitted CO_2 per cargo capacity and distance traveled in a calendar year. This accurately reflects a vessel's total annual CO_2 emissions. The attained CII of a vessel is obtained by

$$CII = \frac{M}{W} \tag{6}$$

where M is the mass of CO_2 emitted and W is the transport work, involving $Capacity$, which in fishing vessels would be taken as the captured biodiversity, and distance sailed. Consequently, a vessel's technical efficiency (EEDI or EEXI) may be superior to another's, yet still achieve an inferior CII due to lower operational volume or higher sailed distance. Fishing vessels typically operate at low speeds while fishing, but consume significant amounts of energy due to the electricity and hydraulic power needed to operate their fishing gear. As a result, the CII value may be impacted and end up higher than that of many merchant vessels.

At present, large fishing vessels such as in the case study meet the criteria for the applicability of the EEDI and EEXI indices since they are of 400 GT and above, but not those for the CII since the IMO only requires this indicator for vessels of 5000 GT and above. If the International Maritime Organization were to follow Europe's steps, as it has done in the past, and equalize the criteria to a minimum of 400 GT, large fishing vessels would be eligible to enter the CII rating system, which will allow their real annual CO_2 emissions to be closely monitored.

Europe has already lowered the gross tonnage requisite so large fishing vessels could be easily included in the MRV system. To implement the annual emissions value and include these vessels in the report and verification scheme (the EU MRV with its amending Regulation (EU) 2023/957 that will be applicable to vessels above 400 GT from January 2025), fuel monitoring methods should be available on board [45,46]. Additionally, in accordance with Regulation (EU) 2015/757 and its amendments in Regulation (EU) 2023/957, access to independent verifiers should be granted to confirm the accuracy of the data provided. Regulation (EU) 2023/957 along with other European developments may result in a future modification of the IMO Carbon Intensity Indicator, which would reduce the applicable gross tonnage from 5000 to 400 GT [42].

The application of an operational indicator could help to allocate CO_2 emissions to the landed fish, obtaining an accurate CO_2 per kilogram of catch and also enabling quantifying the environmental impact of the bycatch, at least for places where landing obligation regulations such as the EU Common Fisheries Policy are in place. Upon successful allocation of CO_2 emissions, market-based strategies can be implemented to encourage the consumption of species with a smaller carbon footprint. In this regard, species with high Fuel Use Intensity or significant bycatch percentage, such as shrimp and lobster, will receive a higher rating [45,82]. This strategy will encourage more sustainable fishing practices by avoiding the targeting of species that are fuel-intensive or result in high rates of bycatch. To do so, several authors agree that fuel monitoring methods should be installed on board fishing vessels [36,45]. And voyage data might be obtained from the Vessel Monitoring System (VMS), mandatory in the main fishing regions [88–90].

5. Conclusions

Decarbonization of the maritime sector cannot be fully achieved without involving all areas of the industry. In the coming future, the responsible organizations shall assess the need to incorporate the fishing sector into energy efficiency regulations to maximize CO_2

abatement. Although Regulation (EU) 2023/957 amended the original Regulation (EU) 2015/757 related to the monitoring, reporting and verification of carbon dioxide emissions from maritime transport, lowering the range from 5000 to 400 GT, this amendment remains inapplicable to fishing vessels. It is important to note that while many fishing vessels are of small size, there is a segment of the fleet that is comparable in size and engine power to cargo vessels subjected to the International Maritime Organization technical energy efficiency indices. And if the IMO were to follow the guidelines outlined by the European Union's Regulation (EU) 2023/957 in the coming future, the operational indicator CII would also apply to many vessels within the fishing fleet.

Even if Regulation (EU) 2023/957 were to apply to fishing vessels, the focal point would be that the equivalent IMO energy efficiency measures (EEDI, EEXI and CII) were implemented. This is because the European Union is only composed of 27 countries, whereas the International Maritime Organization is constituted by 175 member states, with over 100 countries having already ratified the Annex VI of the International Convention for the Prevention of Pollution from Ships (MARPOL). A broader adoption of the energy efficiency measures in the fishing fleet would also result in a more levelled playing field, preventing unevenly matched competition among fishing vessels from different flag states [91].

To demonstrate the importance of including the fishing fleet in the CO_2 reduction strategies, this article compares the attained EIV and EEDI values of two merchant vessels with that of a large-scale purse seine tuna fishing vessel of similar size and power. According to the results, the emissions are worth to consider as the attained EEDI of the studied fishing vessel is up to 3.78 times greater than that obtained for the ferry vessel. Secondly, a comprehensive study of the energy efficiency of eight different purse seine tuna fishing vessels with data from [62] was conducted. Mean EIV and EEXI values of the eight studied vessels were 87.39 and 32.74 $gCO_2/t{\cdot}nm$, respectively. These figures are 7.19 and 3 times higher than the average for merchant vessels ($EIV_{avg{\cdot}merchant}$ = 12.15 and $EEXI_{avg{\cdot}merchant}$ = 10.90 $gCO_2/t{\cdot}nm$). While the sample of vessels is not very large, it is representative of the sector, as vessels of different sizes, from 52 to 105 m in length, and years of construction, from 1976 to 2014, were studied.

Although the current correction factors may favor fishing vessels, their low deadweight compared to similar merchant vessels results in a disadvantage. Due to the particular nature of the fishing industry within the maritime sector, establishing specific correction factors seems to be necessary. Several proposals were put forward in this article in order to hold fishing vessels accountable for the damage of blue carbon deposits, reduction in abundance of the different targeted species and the use of auxiliary vehicles. Additionally, forthcoming research shall explore other correction factors related to fuel tax subsidies and market-based measures.

While the IMO Carbon Intensity Indicator is a very interesting metric that represents the amount of CO_2 released in a calendar year, it was not calculated in this article due to its application only to vessels of 5000 GT and above and the absence of voyage data. To gather reliable data for classifying fishing vessels, on-board fuel monitoring and release of voyage data through the mandatory Vessel Monitoring System shall be implemented.

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Abbreviations

AIS	Automatic Identification System
CII	Carbon Intensity Indicator
CLAV	Tuna Consolidated List of Authorized Vessels
CPUE	Catch-Per-Unit Effort
DCS	IMO Data Collection System
EEDI	Energy Efficiency Design Index
EEXI	Energy Efficiency Existing Ship Index
EIV	Estimated Index Value
EU	European Union
FAD	Fish Aggregating Devices
FUI	Fuel Use Intensity
GHG	Greenhouse Gases
GT	Gross Tonnage
GWP	Global Warming Potential
HFO	Heavy Fuel Oil
IMO	International Maritime Organization
IPCC	Intergovernmental Panel on Climate Change
MARPOL	International Convention for the Prevention of Pollution from Ships
MCR	Maximum Continuous Rating
MEPC	Marine Environment Protection Committee
MRV	EU Monitoring, Recording and Verifying system
RFMO	Regional Fisheries Management Organization
SEEMP	Ship Energy Efficiency Management Plan
VMS	Vessel Monitoring System

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