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A study on measures to reduce greenhouse gases and air pollutants in domestic fishing vessels

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A STUDY ON MEASURES TO REDUCE GREENHOUSE GASES AND AIR POLLUTANTS IN DOMESTIC FISHING VESSELS

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A dissertation submitted to the World Maritime University in partial fulfilment
of the requirements for the award of the degree of Master of Science in
Maritime Affairs

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Declaration

I certify that all the material in this dissertation that is not my own work has been identified, and that no material is included for which a degree has previously been conferred on me.

The contents of this dissertation reflect my own personal views, and are not necessarily endorsed by the University.

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(Date): 25 October 2023

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Abstract

Title of Dissertation: **A study on measures to reduce greenhouse gases and air pollutants in domestic fishing vessels**

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In accordance with the efforts of the International Maritime Organization (IMO) to reduce greenhouse gas and air pollutant emissions from ships, Republic of Korea has also established greenhouse gas (GHG) reduction goals and designated Emission Control Areas (ECA) to mitigate ship exhaust emissions. Fishing vessels within Republic of Korea represent 88.3% of the total ship count, with 88.4% of these vessels falling into the category of small vessels with a tonnage of less than 10 tons. Therefore, efforts have been made to calculate and study methods for reducing exhaust gas emissions from these fishing vessels.

Exhaust gas emissions were categorized into GHG and air pollutants, and calculations were based on existing ship data, classifying emissions by fuel type, tonnage, and propulsion power.

To reduce GHG emissions from fishing vessels, the study opted for battery propulsion based on previous research on ship alternative fuels and utilized the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) methodology. Analyzing the performance of current coastal and offshore fishing vessels, the study estimated the required battery capacity range for building or retrofitting with pure electric propulsion. Using Crystal Ball, the maximum and minimum battery capacities needed were determined and marked on the drawings.

To mitigate air pollutant emissions from fishing vessels, the study focused on installing Exhaust Gas Treatment Systems (EGTS) on small vessels equipped with inboard diesel engines. The study identified installation locations on four types of vessels and calculated their potential impact on stability to make informed decisions.

KEYWORDS: Fishing vessels, Exhaust Gas Treatment Systems, Electric propulsion

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List of Abbreviations

BAU	Business As Usual
CAPEX	Capital expenditure
CAPSS	Clean Air Policy Support System
CH_4	Methane
CO	Carbon monoxide
COP	Conference of the Parties
DOC	Diesel Oxidation Catalyst
DPF	Diesel particulate filters
ECAs	Emission Control Areas
EGTS	Exhaust Gas Treatment System
EG-TIPS	Energy GHG Total Information Platform Service
EPA	Environmental Protection Agency
EU	European Union
GHG	Greenhouse gas
GT	Gross Tonnage
HC	Hydrocarbons
IMO	International Maritime Organization
IPCC	Intergovernmental Panel on Climate Change
KOMSA	Korea Maritime Transportation Safety Authority
KOSIS	Korean Statistical Information Service
MDO	Marine Diesel Oil
MEPC	Marine Environment Protection Committee
MGO	Marine Gas Oil
NH_3	Ammonia
NAEIR	National Air Emission Inventory and Research Center
NIER	National Institute of Environment Research
NM	Nautical Miles
NMVOCs	Non-methane volatile organic compounds
NO_x	Nitrogen oxides
OPEX	Operating expenditure
PM	Particulate matter
SCRF	Selective Catalytic Reduction Filter
SO_2	Sulfur dioxide
SOF	Soluble Organic Fraction
TOPSIS	Technique for Order of Preference by Similarity to Ideal Solution
UNFCCC	United Nations Framework Convention on Climate Change

Chapter 1. Introduction

1.1 Background

In a world where 80% of global merchandise trade is transported by ships (UNCTAD, 2019), ship emissions contribute significantly to the total artificially generated emissions, with the potential to increase alongside the expansion of international maritime trade (Aksoyoglu et al., 2016; Becagli et al., 2017; Endresen et al., 2003). Major air pollutants associated with ship emissions include carbon monoxide (CO), nitrogen oxides (NO_x), sulfur dioxide (SO_2), particulate matter (PM), and non-methane volatile organic compounds (NMVOCs) (EMEP/EEA 2013). These substances are known to have adverse effects on human health and global climate change (Aksoyoglu et al., 2016; Capaldo et al., 1999; Corbett et al., 1999; Firlag et al., 2018; Jalkanen et al., 2012; Winther et al., 2014). Due to these environmental concerns, the International Maritime Organization (IMO) has strengthened regulations on emissions of NO_x, SO_x, and PM from ships through the MARPOL Annex VI treaty (IMO, 2019; Ölçer et al., 2018). Republic of Korea has also made efforts to manage ship emissions by implementing the "Special Act on Improving Air Quality in Port Areas and Others" since January 2020, which enforces stricter sulfur content standards for ship fuels (0.1%) in Emission Control Areas (ECAs) compared to 0.5% in open seas (DNV·GL, 2020).

Concurrently, various technologies are being developed to reduce particulate matter (PM) emissions and soot from ship engines. Prominent technologies include scrubber, diesel particulate filter (DPF), and electrostatic precipitator (Chun et al., 2010; Stamatellou & Stamatelos, 2017; Tang et al., 2014). The scrubber technology reduces sulfur oxides in exhaust gases using washwater and can also mitigate PM and soot emissions. However, this technology is primarily applied to large vessels due to the need for additional washwater treatment systems beyond the scrubbing system. Exhaust Gas Treatment System (EGTS) such as DPF systems, on the other hand, are applied to small and medium-sized vessels in response to regulations on fine dust emissions enforced by European regulations for ships navigating domestic and near-coastal waters and enhanced fine dust regulations by the U.S. EPA (Dieselnet, 2023). On the global scale, as concerns regarding global warming caused by greenhouse gas (GHG) emissions persist, efforts to accurately assess GHG emissions from various industries and reduce emissions are ongoing. As a part of these efforts, in countries designated as mandatory reduction countries under the Kyoto Protocol adopted at the United Nations Framework Convention on Climate Change (UNFCCC) Conference of the Parties (COP) held in Kyoto, Japan in 1997, GHG reduction has become a prominent issue across various industries, leading to extensive research. In 2015, at the 21st UNFCCC COP held in Paris, Republic of Korea committed to reducing its GHG emissions by 37% by 2030 compared to Business As Usual (BAU) levels (Bae et al., 2019). In the fisheries sector, efforts continue to reduce atmospheric pollution from fishing vessels, with a goal to reduce GHG emissions from the fisheries sector by 70% compared to 2018 levels by 2030, as part of the "Marine and Fisheries Sector 2050 Carbon Neutrality Roadmap" (MOF, 2021).

1.2 Problem Statement

According to Republic of Korea's marine and fisheries statistics as of 2022, the total number of registered vessels is 72,077, of which general vessels account for 8,408, while fishing vessels comprise 63,669, representing 88.3% of the total vessels (MOF, 2023). Due to the significant number of fishing vessels, it is important to note that, for a more detailed understanding of vessel specifications, as of May 2023, when checking the fishing vessels subject to inspection by the Korea Maritime Transportation Safety Authority (KOMSA), there are 64,259 vessels in total. Among these, small fishing vessels less than 10 tons and using fossil fuels account for 56,807 vessels, approximately 88.4% of the total fishing vessels. Thus, while the management of small fishing vessels is crucial, most research aimed at preventing atmospheric pollution from ships has primarily focused on larger vessels, emphasizing emission calculations and reduction technologies.

1.3 Motivation

In Republic of Korea, efforts have been made to address GHG emissions from fishing vessels, which account for the majority of emissions in the fisheries sector. These efforts include replacing aging government-owned vessels with low-carbon vessels. However, the number of such replacements is limited, and therefore, GHG reduction measures are needed for the entire fishing vessel fleet.

On the other hand, small vessels primarily used in coastal fishing and cargo transport have been identified as direct sources of pollution in ports and their vicinity. This has led to a trend of regulating the total emissions of pollutants. Consequently, there is a demand for the installation of appropriate EGTS on small vessels. To install EGTS, some degree of space, such as in the engine room, is required. However, small vessels often face challenges in securing the necessary installation space. Therefore, there is a practical need for optimizing EGTS in terms of space utilization for small vessels. Furthermore, there is a need for EGTS that can maximize operational efficiency by optimizing their performance based on the vessel's operating conditions. In response to these needs, the KOMSA has patented a ship-specific EGTS that effectively utilizes limited space, especially on small vessels where space for exhaust purification devices is limited (Seong et al., 2022). Therefore, in this study, in addition to measures for GHG reduction in domestic vessels, options for installing EGTS on small ships, particularly small fishing vessels with less than 10 tons, will be considered.

1.4 Aims and Objectives

This study aims to examine strategies for reducing GHG (CO_2, CH_4, N_2O) and air pollutants (PM, NO_x, SO_2, CO) from domestic fishing vessels in Republic of Korea. Firstly, it aims to assess the overall amount of GHG emissions from domestic fishing vessels and explore strategies for their reduction. To mitigate GHG emissions, it investigated the most appropriate technologies and assess their applicability to fishing vessels. Subsequently, the study was examined methods for installing EGTS on small fishing vessels less than 10 tons, which are equipped with inboard diesel engines and represent the largest segment of vessels in Korea, to reduce pollutant emissions. It proposed installation methods for several types of small vessels and assess the impact on sustainability resulting from the implementation of these systems.

1.5 Research Questions

- How much GHG and air pollutants emitted from fishing vessels?
- What are the methods to reduce GHG and air pollutants from Republic of Korean fishing vessels?
- What are the main considerations for conceptual design when applying electric power propulsion to fishing vessels?
- What is the EGTS installation model suitable for small fishing vessels and what is the impact on stability when installing it?

1.6 Hypotheses

For this study, the following hypotheses have been formulated:

- The air pollutant emissions from small fishing vessels with a total tonnage of less than 10 tons were greater than those from fishing vessels with a tonnage of 10 tons or more.
- To reduce GHG emissions from fishing vessels, it is possible to review existing technologies and find the optimal methods.

- EGTS can be installed on small fishing vessels, and their stability can be ensured even after installation.

1.7 Key assumptions and potential Limitations

In this study, due to the nature of small fishing vessels, precise route information is unavailable, making it challenging to accurately determine air pollutant and GHG emissions from these vessels. Furthermore, the effect of reducing atmospheric pollutants from small fishing vessels by installing EGTS can only be estimated approximately. Post-installation, the composition of atmospheric pollutants cannot be precisely determined, as it can only be assessed using filter smoke numbers. However, literature reviews have shown instances of using DPF in previous experiments, providing a basis for predicting the reduction in atmospheric pollutants from vessels.

Additionally, in the conceptual design of EGTS suitable for small vessels, validation of their effectiveness was based on actual ship drawings and stability calculation data. However, designing an EGTS with precise consideration of the primary engine's capacity may prove difficult in this research. Hence, with reference to the findings of this study, more detailed designs will be feasible during the detailed design phase.

Moreover, overall GHG reduction for the entire fishing industry should be considered separately from the application of exhaust gas reduction systems for small vessels. It should be reviewed in conjunction with the broader aspects of the industry in the future.

1.8 Research Structure and Organization

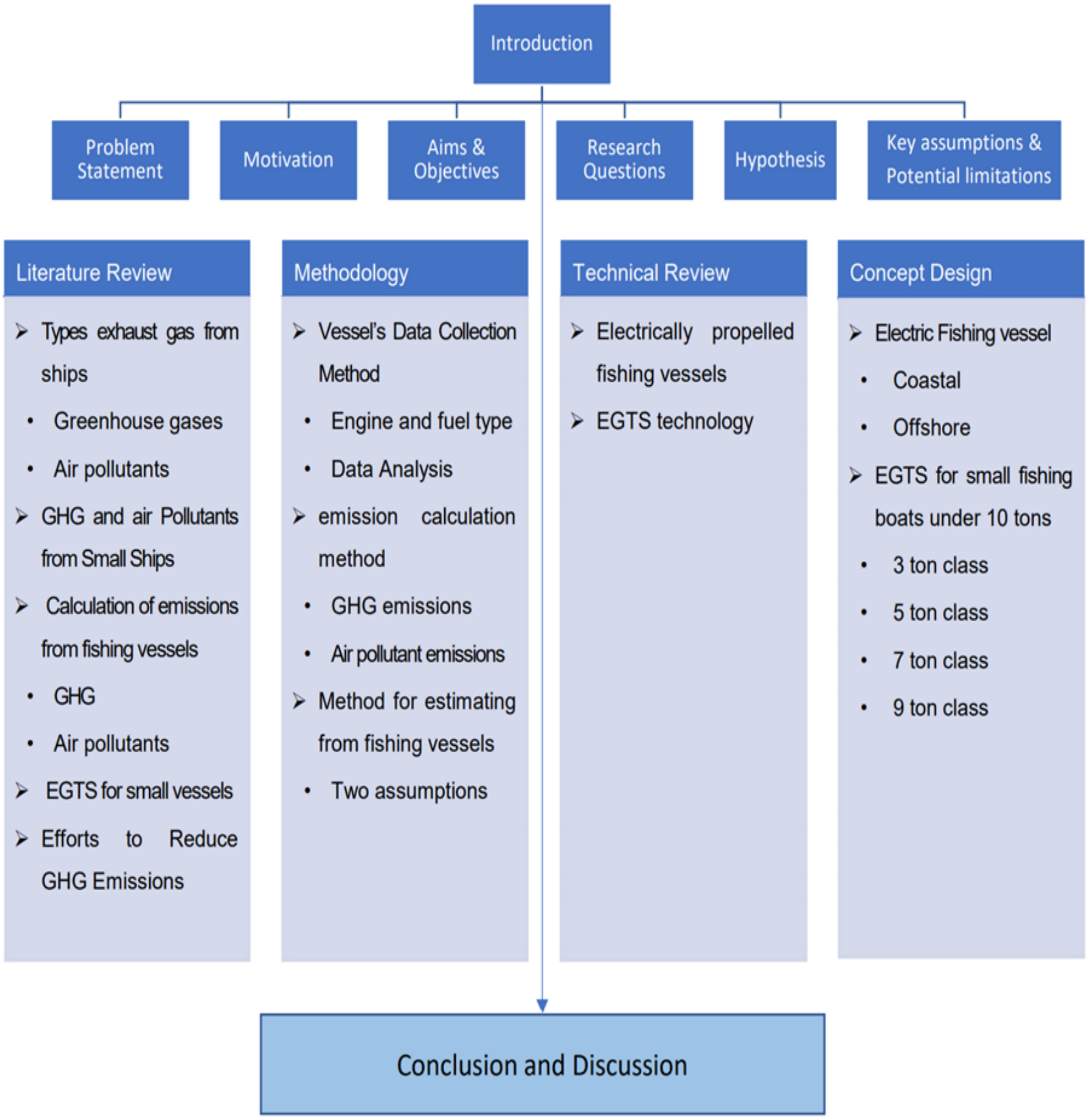


Figure 1: Research process workflow (Author, 2023)

Chapter 2. Literature Review

This chapter aims to explore the types of GHG and air pollutants emitted from ships and examine the regulations in place to mitigate these emissions. Additionally, it delves into the types of GHG and air pollutants emitted by small fishing vessels operating within the country, which are often excluded from regulations, and assesses their environmental impact. Furthermore, it investigates methods for calculating emissions from small fishing vessels and introduces strategies and exhaust gas reduction systems to reduce these emissions.

2.1 Types and emissions of exhaust gases from ships

2.1.1 GHG

In the case of ships, during fishing operations and navigation, GHG such as carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) are emitted. Data on these emissions can be obtained from sources like the GHG Inventory & Research Center of Korea (ME, 2023), the Energy GHG Total Information Platform Service (EG-TIPS, 2023), and the Korean Statistical Information Service (KOSIS, 2023). In 2018, direct emissions from the use of marine fuels in Republic of Korea's domestic shipping amounted to 1.019 million tons, with direct emissions from fishing vessels reaching 2.538 million tons. This accounts for the majority, approximately 83.4%, of the total emissions in the fisheries and coastal sector, totaling 3.042 million tons (The Government of the Republic of Korea, 2020; Hong, 2022).

2.1.2 Air Pollutants

In Republic of Korea, the national atmospheric pollutant emissions are calculated using the Clean Air Policy Support System (CAPSS) of the National Air Emission Inventory and Research Center (NAEIR, 2023), as noted by Lee et al. (2020). According to the recent report from the NIER (2018), the total emissions from ships (CO, NO_x, SO_x, PM10, PM2.5, VOCs, NH_3, BC) account for 6.4% of the total national emissions. Of these, NO_x constitutes 13.1%, SO_x 10.9%, and particulate matter (PM10/PM2.5) 9.6%. Among the emissions from ships, cargo ships engaged in domestic and international trade account for 50.6%, indicating the substantial contribution of fishing vessels at 42.6% (Lee et al., 2017). Table 1 below presents a summary of the atmospheric pollutant emissions by ship type. It reveals that emissions are highest for cargo ships, followed by fishing vessels and passenger ships. Fishing vessels, in particular, hold a significant share, constituting 88% of all vessels, indicating their substantial contribution (KOSIS, 2023).

Table 1: Amount of air pollutant emission by vessel type (Lee et al., 2020)

unit : ton

Subclass	CO	NOx	SOx	PM10	PM2.5	VOCs	NH3	BC
Total	**60,491**	**151,735**	**38,467**	**7,091**	**6,539**	**20,970**	**14**	**1,042**
Ferry	692	7,361	1,248	255	233	259	0.7	43
Cargo	8,032	85,767	36,698	4,904	4,447	2,969	7.6	637
Fishingboat	45,640	58,564	519	1,771	1,697	14,773	5.3	353
Leisureboat	6,125	41	-	160	160	2,967	0.1	8

* Total is rounded at the first decimal place, and it is different with thesum of numbers by vessel type.

2.2 GHG and Air Pollutants Emitted from Small Ships (types, effects)

Despite the fact that small ships, with a gross tonnage of less than 10 tons, account for 95% of Republic of Korea's ships, the country's ship management primarily focuses on larger vessels with over 100 tons. Consequently, significant emissions of PM and gaseous atmospheric pollutants from small ships go unregulated (Kim et al., 2022). An analysis of the emissions situation from small ships, which remains a blind spot in fine PM management, reveals that NO_x emissions are 22 times higher compared to previous emission levels. Moreover, PM emissions are tens to hundreds of times higher than those from roadside particles (Cho et al., 2019; Wang et al., 2008). Currently, there are no regulations addressing these emissions. Considering the minimum individual emission levels identified in this study, the application of selective catalytic reduction (SCR) or DPF, similar to those used in diesel vehicles designated as emission sources of Group 1 carcinogens, seems necessary. Policymaking and technology development were required to address this issue in the future (Kim et al., 2022).

On the other hand, regarding GHG, direct emissions from fishing vessel fuel use in Republic of Korea in 2021 were reported as 2.538 million tons in the "2050 Carbon Neutrality Roadmap for Marine Fisheries" policy report by the Ministry of Oceans and Fisheries (MOF, 2021). However, sources other than this report provide limited information on GHG emissions specific to fishing vessels.

2. 3 Calculation of GHG and pollutant emissions from fishing vessels

2.3.1 GHG from fishing vessels

Coastal and offshore fishing activities exhibit varying engine load factors depending on factors such as the specifications of the vessel, its horsepower, tonnage, the captain's operational style, and the vessel's activity. Moreover, some vessels manipulate their wireless equipment falsely, making it difficult to accurately measure engine operating time. Therefore, the Tier 1 level GHG emission calculation methodology, which utilizes fuel consumption data by fuel type and emission factors by fuel type and GHG, is a useful approach for applying to a wide range of 24 fishing sectors. To estimate the emissions of CO_2, methane (CH_4), and nitrous oxide (N_2O) from fishing vessels, fuel consumption was substituted for fuel supply, and CO_2 emissions were estimated using the calculation formula provided by the "Energy GHG Comprehensive Information Platform." CH_4 and N_2O emissions were estimated using the formulas proposed in the "2019 National GHG Inventory Report."

Equation (1) below represents the calculation formula for CO_2 emissions from fishing vessels by sector and fuel type, with FS denoting fuel consumption, NCV representing net calorific value, CEF signifying the carbon emission factor, i representing the 24 sectors, and j representing the fuel type (gasoline, diesel, heavy oil). The constants 10^6 and 44/12 are used to convert CO_2 emissions to tons and carbon emissions to CO_2 emissions, respectively.

$$CO_2\ Emissions_{ij}(t) = FS_{ij} \times NCV_j \times CEF_j \times 10^{-6} \times \frac{44}{12} \qquad (1)$$

Equations (2) and (3) represent the calculation formulas for CH_4 and N_2O emissions from fishing vessels by sector and fuel type, with CF_j denoting the conversion factor, EF_j (CH_4) and EF_j (N_2O) representing the emission factors for CH_4 and N_2O. The constants 10^3 and 41.868 are used to convert CH_4 and N_2O emissions to tons and to convert fuel supply, expressed in TOE (ton of oil equivalent), to joules, respectively.

$$CH_4\ Emissions_{ij}(t) = FS_{ij} \times 41.868 \times CF_j \times EF_j(CH_4) \times 10^{-3} \qquad (2)$$

$$N_2O\ Emissions_{ij}(t) = FS_{ij} \times 41.868 \times CF_j \times EF_j(N_2O) \times 10^{-3} \qquad (3)$$

The estimated CH_4 and N_2O emissions, obtained from equations (2) and (3), are subsequently converted to CO_2 equivalents using global warming potentials of 21 and 310, respectively, for use in efficiency analysis. These global warming potentials signify that CH_4 and N_2O have 21 and 310 times greater global warming effects than CO_2, respectively (Jeon & Nam, 2021).

2.3.2 Air pollutants from fishing vessels

Research related to ship air pollutant emissions has been actively conducted in Europe, the United States, and some Asian countries (Berechman and Tseng, 2012; Deniz and Kilic, 2009; Ledoux et al., 2018; Maragkogianni and Papaefthimiou, 2015; Nunes et al., 2017; Port of Los Angeles, 2022; Saxe and Larsen, 2004; Tichavska and Tovar, 2015; Wan et al., 2019; Yau et al., 2013). In Republic of Korea, research focused on trading ports has been carried out using ship specification data (Chang et al., 2014; Khan et al., 2018; Kim and Shin, 2014; Park et al., 2011; Song and Shon, 2014; Zhao et al., 2019). However, both domestic and international studies on ship emission estimation have often centered on specific ports, leading to a lack of comprehensive analyses regarding the contribution of ships to the national emission total. To address this gap, this study utilized complete vessel specifications for passenger ships, cargo ships, and fishing vessels operating within Republic of Korea. It calculated and updated emissions of air pollutants as of 2015, considering the national context. Inland waterways such as rivers and lakes were excluded from the emission sources. To achieve this, a novel methodology was developed. It involved analyzing transit times between ports, sailing routes, and actual fuel consumption at sea, while applying emission factors categorized by ship type and fuel type. Furthermore, emissions were scrutinized to distinguish between port emissions and emissions in marine areas by analyzing data from individual ports and shipping routes (Seol et al., 2021).

Fishing vessels were assessed in this study, focusing on domestic coastal and offshore vessels. Data regarding fuel consumption, categorized by regional cooperatives under the central union of fisheries, were matched with inspection data from the KOMSA, and emission factors were applied. To account for emissions related to vessel idling in ports, 5% of fuel consumption was assumed and incorporated into the methodology. Additionally, due to the lack of route information for individual fishing vessels, the study relied on fishery habitat formation data from domestic research (NIER, 2015) to identify the areas where these vessels directly operated, ultimately calculating emissions for 348 fishing grounds below Table 2.

Table 2: 2015 emissions by vessel type.

(Unit: tons/year)

Sauce	**CO**	**NO_x**	**SO_x**	**PM-10**	**PM-2.5**	**Volatile organic compounds (VOCs)**
Passenger Ships	692	7,361	1,249	255	233	259
Cargo Ship	8,033	85,768	36,699	4,904	4,447	2,970
Fishing boat	45,641	58,564	519	1,772	1,698	14,773
sum	54,366	151,693	38,467	6,931	6,378	18,002

For fishing vessels, the analysis revealed harbor emissions of 2,282 tons per year (5.0%) according to CO in table 2, while sea emissions accounted for 43,359 tons per year (95.0%). Within the total emissions, those attributed to gasoline use amounted to 40,182 tons per year, representing 88.0%. It's worth noting that actual fuel consumption for diesel was approximately 8.9 times higher than for gasoline. However, this contrasting result is believed to be due to differences in emission factors (Seol et al., 2021). Unlike passenger and cargo vessels, fishing vessels lacked route information, which posed limitations when calculating emissions based on operational characteristics and route origins. In the domestic fishing vessel sector, data management, including routes and operational patterns, was challenging, resulting in limited detail in emission statistics. Moreover, fishing vessels accounted for approximately 94% of the registered vessel population (Kim et al., 2014). Therefore, it is estimated that if diverse source data were available, the contribution of fishing vessels to air pollutant emissions would be greater compared to other types of vessels (Seol et al., 2021).

2. 4 EGTS for small vessels

The application of EGTS for small and medium-sized vessels is being pursued in Europe for inland and coastal shipping, in response to regulations on particulate matter emissions and strengthened regulations by the United States Environmental Protection Agency (EPA) (Lee et al., 2017).

In the case of diesel engines used in ships, the reduction efficiency of PM and soot emissions through the application of DPF varies depending on the measurement method. When measured using a dilution-based method, the reduction efficiency of particulate matter was found to range from a minimum of 76% to a maximum of 91% depending on the engine operating conditions. In contrast, the reduction efficiency of soot (black carbon), calculated as the product of the PM's composition ratio and mass concentration, exceeded 90%. Furthermore, when a smoke meter applying optical absorption was used to measure the reduction efficiency of soot, it consistently showed over 90% reduction efficiency under all operating conditions. Additional measurements using an opacity meter resulted in a maximum reduction efficiency of 80%. In conclusion, the feasibility of applying DPF as a mitigation technology for reducing PM and soot emissions from small vessels has been confirmed (Lee et al., 2017).

2. 5 Technical Efforts to Reduce GHG Emissions from Fishing Vessels

Chapter 2.5.1 Resistance component of fishing vessels

Generally, the majority of a ship's resistance is attributed to frictional resistance and wave resistance components. As the ship's speed decreases, the proportion of wave resistance in the total resistance increases, while at higher speeds, the importance of frictional resistance grows. Figure 2 provides a comparative analysis of the relative sizes of key resistance components for several types of vessels. The horizontal axis represents the percentage of each resistance component in the total resistance, and the approximate value of the total resistance coefficient $C_T = R_T \frac{1}{2}\rho S V^2$ is indicated in the lower right corner of each horizontal bar. Here, R_T denotes total resistance, ρ represents fluid density, V stands for the ship's velocity, and S denotes the immersed surface area of the ship (SNAK, 2011). Fishing vessels, although generally characterized by significant wave resistance, can also consider other forms of resistance, such as water spray resistance and appendage resistance, especially in the case of small fishing vessels. For instance, Asian fishing vessels often have different hull forms compared to European counterparts, tending to be longer and faster. This is also evident through the Equivalence of Length to gross tonnage (GT) system, recognized in the Cape Town Agreement, which designates vessels over 24 meters and 300 GT (IMO, 2023). Consequently, it can be inferred that Asian fishing vessels often include high-speed hull forms. Hence, it is common to consider not only Wave Resistance and Viscous Resistance but also Spray Resistance and Appendage Resistance when assessing the resistance experienced by fishing vessels.

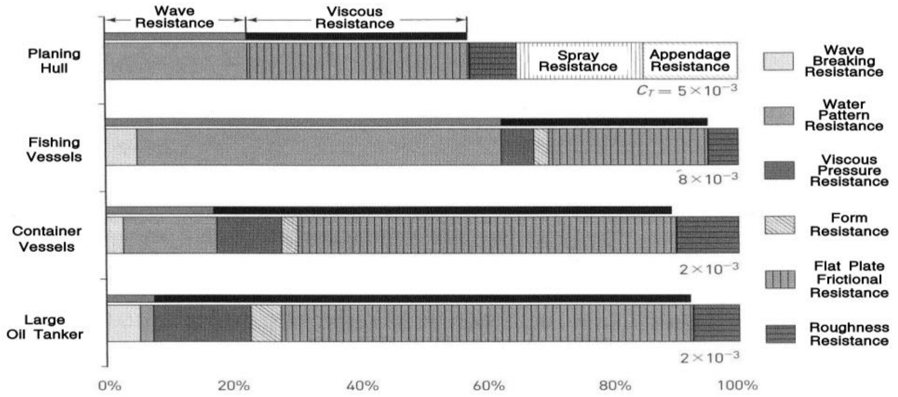


Figure 2: Relative size of resistance component (SNAK, 2011, p. 156)

2.5.2 Resistance reduction through hull shape optimization

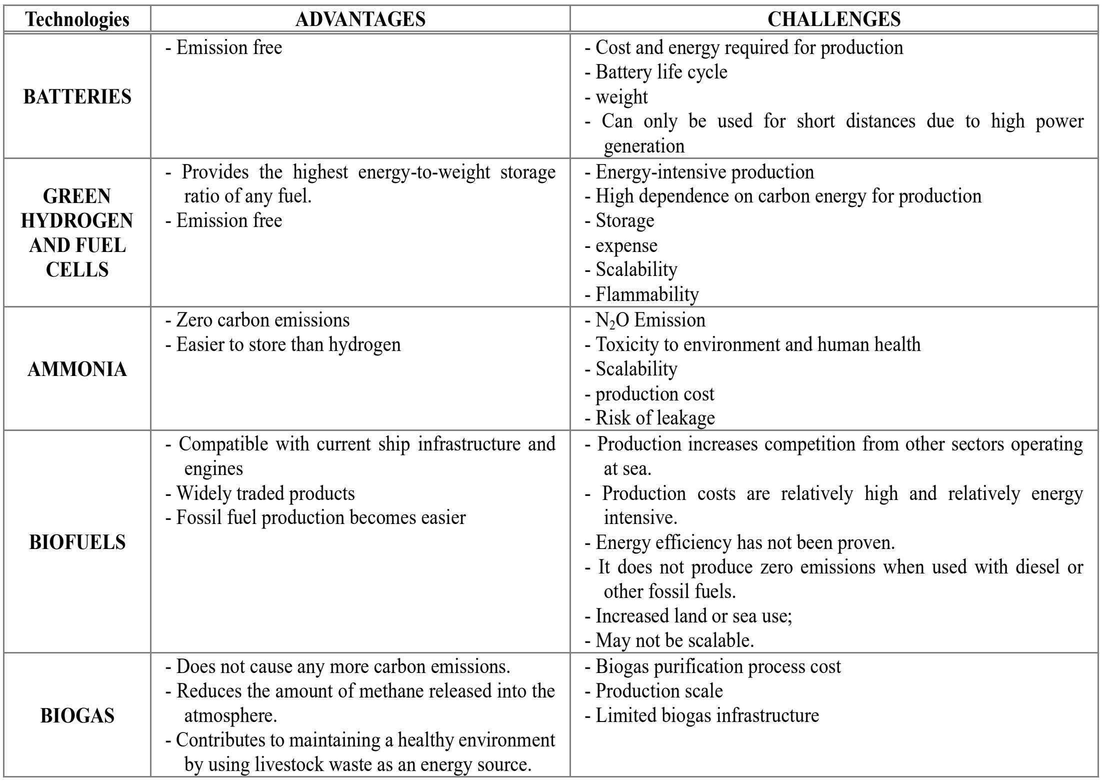
The trim position of a high-speed ship significantly affects its resistance. Efforts have been directed towards mitigating unstable pressure distribution along the lower hull due to high-speed operations and resistance issues arising from excessive stern trim. Seo et al. (2005) reported that installing an appendage capable of generating lift at the stern could lead to a 3% to 10% reduction in resistance by adjusting stern trim by 1 to 3 degrees, contingent upon the appendage type and form. The stern wedge, situated below the transom and shaped like a wedge, enhances stern trim by facilitating pressure recovery and lift generation. Karafiath & Fisher (1987) ascertained that the degree of resistance reduction ranged from 4% to 12% within the range of $0.5 < Fn < 0.9$ (where Fn signifies the Froude number), contingent upon the length of the stern wedge and the angle formed by the hull and the appendages. In the instance of a stern flap, characterized by a flat plate at the transom's rear, it effectively extends the hull's length in that area, thereby engendering an effect analogous to the stern wedge in terms of bolstering resistance performance. Moreover, the introduction of a stern flap amplifies the flow velocity beneath the transom's trailing edge upon installation. This augmented velocity retards flow separation and consequently diminishes viscous resistance. Additionally, according to Yaakob et al. (2004), the stern flap not only surpasses the performance of the stern wedge but also obviates the need for slot welding. Recent research conducted by Lee et al. (2021) showcased a 9.29% reduction in resistance and a 7.05% drop in effective horsepower by affixing a stern flap onto coastal fishing boat.

2.5.3 Review of available alternative technologies for decarbonization of fishing vessels

2.5.3.1 Consideration of Carbon Reduction in European Fishing Vessels

In an effort to reduce fossil fuel dependency and participate in energy transition, the European Commission initiated the Green Deal in 2020. However, the fisheries sector still heavily relies on fossil fuel subsidies and fossil fuels, and there is a lack of strategies or roadmaps to address this issue. Therefore, an analysis was conducted to determine if the innovations occurring in the shipping sector could be applicable to the fisheries sector, as presented in the following Table 3 (Ferdous & Tacconi, 2022).

Table 3: 2015 emissions by vessel type (Ferdous & Tacconi, 2022)

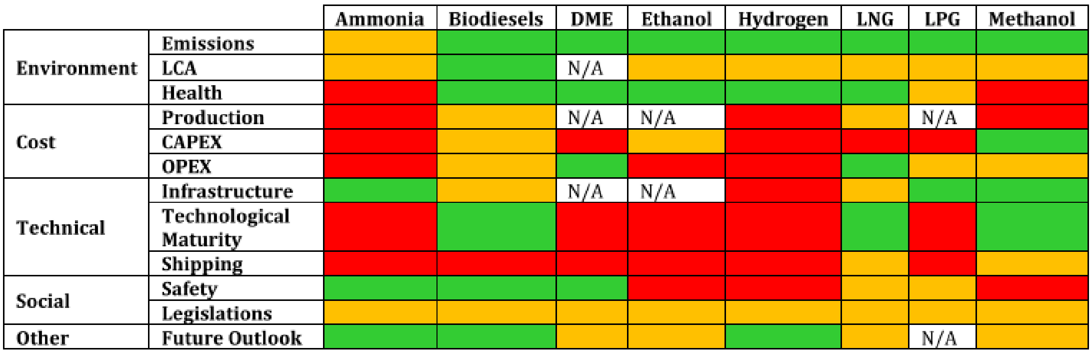


Technologies	ADVANTAGES	CHALLENGES
BATTERIES	- Emission free	- Cost and energy required for production - Battery life cycle - weight - Can only be used for short distances due to high power generation
GREEN HYDROGEN AND FUEL CELLS	- Provides the highest energy-to-weight storage ratio of any fuel. - Emission free	- Energy-intensive production - High dependence on carbon energy for production - Storage - expense - Scalability - Flammability
AMMONIA	- Zero carbon emissions - Easier to store than hydrogen	- N_2O Emission - Toxicity to environment and human health - Scalability - production cost - Risk of leakage
BIOFUELS	- Compatible with current ship infrastructure and engines - Widely traded products - Fossil fuel production becomes easier	- Production increases competition from other sectors operating at sea. - Production costs are relatively high and relatively energy intensive. - Energy efficiency has not been proven. - It does not produce zero emissions when used with diesel or other fossil fuels. - Increased land or sea use; - May not be scalable.
BIOGAS	- Does not cause any more carbon emissions. - Reduces the amount of methane released into the atmosphere. - Contributes to maintaining a healthy environment by using livestock waste as an energy source.	- Biogas purification process cost - Production scale - Limited biogas infrastructure

2.5.3.2 Alternative Fuels for Fishing Vessels

According to Bilgili (2023), the utilization of alternative fuels has both advantages and disadvantages. These have been evaluated and color-coded in the following Table 4 for reference. Green indicates high availability and compatibility of the fuel, orange indicates compatibility issues that need to be overcome, and red indicates early-stage development (Bilgili, 2023).

Table 4: Final evaluation of alternative fuels (Bilgili, 2023).



		Ammonia	Biodiesels	DME	Ethanol	Hydrogen	LNG	LPG	Methanol
Environment	**Emissions**	🟧	🟩	🟩	🟩	🟩	🟩	🟩	🟩
	LCA	🟧	🟩	N/A	🟧	🟧	🟧	🟧	🟧
	Health	🟥	🟩	🟩	🟩	🟩	🟩	🟧	🟥
Cost	**Production**	🟥	🟧	N/A	N/A	🟥	🟧	N/A	🟥
	CAPEX	🟥	🟧	🟥	🟧	🟥	🟥	🟥	🟩
	OPEX	🟥	🟧	🟩	🟥	🟥	🟩	🟧	🟧
Technical	**Infrastructure**	🟩	🟧	N/A	N/A	🟥	🟧	🟩	🟩
	Technological Maturity	🟥	🟩	🟥	🟥	🟥	🟩	🟥	🟩
	Shipping	🟥	🟥	🟥	🟥	🟥	🟧	🟥	🟧
Social	**Safety**	🟩	🟩	🟩	🟥	🟥	🟧	🟧	🟥
	Legislations	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧
Other	**Future Outlook**	🟩	🟩	🟧	🟧	🟩	🟧	N/A	🟧

Generally, alternative fuels have not yet reached the desired levels of development, production for marine use is limited, and comprehensive research is still lacking.

Chapter 3. Research Methodology

This chapter discusses the methodology to be employed in the dissertation. Firstly, it involves collecting and analyzing existing data from domestic fishing vessels and reviewing the methods for calculating GHG and air pollutant emissions from these vessels. To estimate emissions of GHG and pollutants from Korean fishing vessels, two assumptions are made, taking into account the practical difficulties of knowing their navigation routes. Fuel consumption is calculated by determining a Factor for each kW, assuming that the product of a vessel's kW and factor represents fuel consumption. This is done to align vessel kW-specific emissions with the GHG and air pollutant emission data provided by the Ministry of Environment in Republic of Korea, establishing their relationship.

Next, to explore the most suitable alternative propulsion methods for reducing GHG emissions in fishing vessels, battery propulsion is added to Table 2 in Chapter 2.5.3.2. The Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) methodology is then used to identify the most suitable propulsion method for fishing vessels.

3.1 Vessel's Data Collection Method

3.1.1 Vessel's Data Collection by Engine and fuel type

The most recent data related to domestic fishing vessels were collected from the KOMSA, which oversees the inspection of vessels. As of May 2023, there were a total of 64,259 vessels under inspection. Among these, 93.9%, or 60,360 vessels, were small fishing vessels with a tonnage of less than 10 tons. After excluding ocean-going vessels and electric propulsion vessels, the focus was placed on vessels using gasoline and diesel engines. This resulted in a total of 60,191 vessels, with 56,807 being small fishing vessels with a tonnage of less than 10 tons.

Therefore, as illustrated in Figure 3, when examining the distribution of vessels by tonnage, it becomes evident that the majority of vessels fall within the 1 to 2 ton category, while vessels with a tonnage of 50 tons or more are relatively scarce.

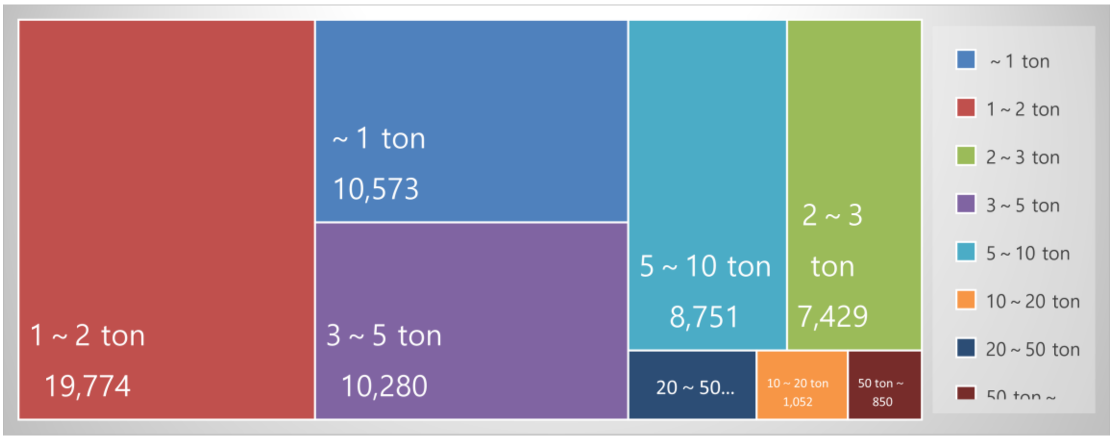


Figure 3: Number of small fishing boats under 10 tons using gasoline and diesel propulsion engines

3.1.2 Vessel's Data Analysis by Engine and fuel type

The types of fuels for vessel propulsion, gasoline, and diesel, are classified by vessel tonnage according to their propulsion methods. Among these, vessels in the 1~2 tonnage range are the most numerous, totaling 19,774 vessels, while vessels over 50 tons are the least numerous, with 850 vessels. Concerning average output, as tonnage increases, so does the average output, but the 20~50 ton range has lower average output compared to the 10~20 ton range. Analysis regarding fuel usage and installation methods can be observed in Figure 4 below. Vessels using gasoline as fuel are mostly ships under 2 tons, totaling 25,192 vessels, and the majority of these vessels have Outboard engine types. Although the average horsepower varies widely, ranging from about 40~210 kW for vessels under 20 tons, only Inboard-type vessels are eligible for exhaust gas reduction system installation. Therefore, gasoline engines, most of which are Outboard type, are excluded from the scope of EGTS installation and are only addressed in relation to GHG.

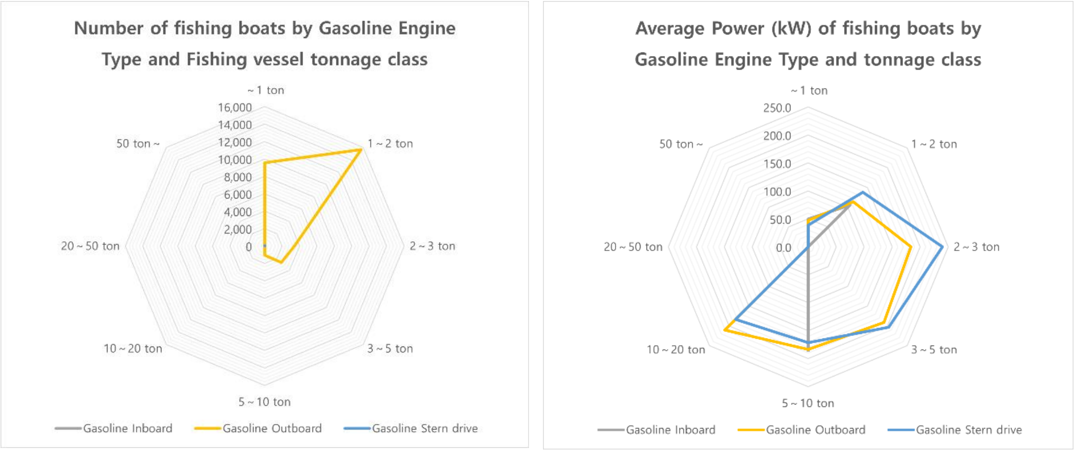


Figure 4: Number of boats and average power according to tonnage class of fishing vessel by Gasoline Engine and types

Furthermore, as shown in Figure 5, for Diesel Engines, the majority of small vessels under 10 tons are of the Inboard type with engine rooms, and their power ranges from 40 to 450 kW, making it possible to consider the installation of an EGTS. Therefore, one of the objectives of this study is to limit the installation of EGTS to small vessels under 10 tons with Inboard-type Diesel Engines.

In the end, vessels with Diesel Engines installed, as opposed to gasoline propulsion engines, have a greater number of Inboard-type propulsion systems. Thus, when installing EGTS, it can be anticipated that the reduction in fine PM emissions would be higher. However, GHG emissions apply to all vessels using fossil fuels, so GHG reduction methods for all vessels would also be examined.

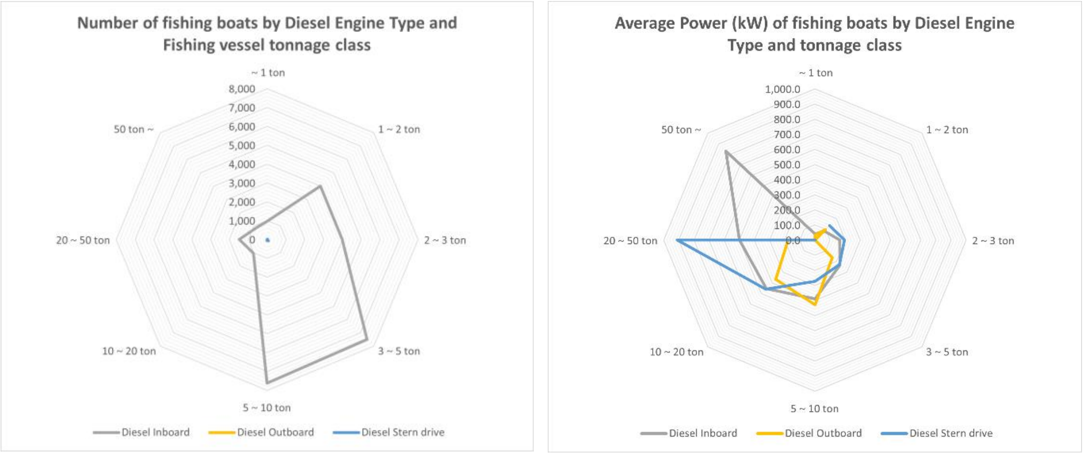


Figure 5: Number of boats and average power according to tonnage class of fishing vessel by Diesel Engine and types

3.2. Review of GHG and air pollutant emission calculation method

3.2.1 Method of calculating GHG emissions

According to the Intergovernmental Panel on Climate Change (IPCC, 2023), the process of calculating and quantifying GHG emissions and absorptions is referred to as national GHG inventory estimation. This inventory estimation methodology categorizes the estimation levels into Tier 1, Tier 2, and Tier 3, based on the specificity of activity data, emission/absorption factors, and application methods. Tier 1 represents the basic methodology of calculating emissions using IPCC default emission factors and activity data, including basic oxidation factors and heat values.

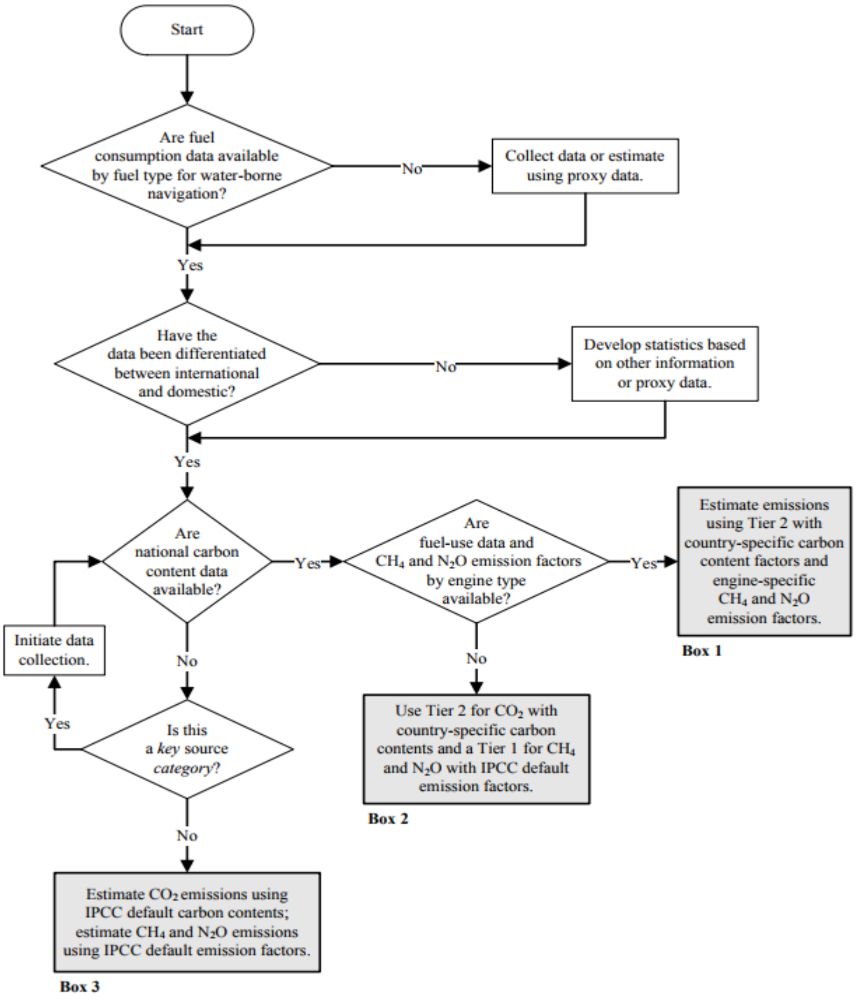


Figure 6: Decision tree for emissions from water-borne navigation (IPCC 2006)

Tier 2 involves a more accurate emissions estimation methodology that utilizes activity data with higher accuracy and parameters developed through testing and analysis, such as national-specific emission factors and heat values. Tier 3 represents an emissions estimation methodology with even higher accuracy than Tier 1 and Tier 2, utilizing activity data with superior accuracy and parameters developed through testing and analysis conducted by operators or obtained from suppliers. The IPCC 2006 Guidelines provide advice on estimation methods across these three detailed levels, from Tier 1 to Tier 3.

However, according to IPCC 2006's section on water-borne navigation (3.5), as shown in Figure 6, only Tier 1 and Tier 2 are presented for water-borne navigation, and there is no guidance provided for Tier 3 in this context.

In this study, due to the lack of consideration for country-specific emission factors with greater specificity in the classification of engine types, Tier 1 was applied. The Tier 1 method's fuel consumption data and emission factors depend on the type of fuel, so the calculations are based on the amount of combusted fuel and the emission factors for CO_2, CH_4, and N_2O. The calculation formula is as follows:

$$Emissions = \sum (Fuel\ Consumed_{ab} \bullet Emission\ Factor_{ab})$$

Where:

a = fuel type (diesel, gasoline, LPG, bunker, etc.)

b = water-borne navigation type (i.e., ship or boat, and possibly engine type.) (Only at Tier 2 is the fuel used differentiated by type of vessel so b can be ignored at Tier 1)

To convert fuel consumption into energy units, calorific values are required. IPCC guidelines use net calorific values (NCV), as shown in Table 5.

Table 5: Default Net Calorific Values (NCVs) and Lower and Upper Limits of the 95% Confidence Intervals (IPCC 2006)

Fuel type English description		Net calorific value (TJ/Gg)	Lower	Upper
Gasoline	Motor Gasoline	44.3	42.5	44.8
	Aviation Gasoline	44.3	42.5	44.8
	Jet Gasoline	44.3	42.5	44.8
Gas/Diesel Oil		43.0	41.4	43.3

The basic CO_2 emission factors below Table 6 are based on the fuel type and carbon content, considering the oxidized carbon ratio (100%).

Table 6: CO_2 Emission factors (IPCC 2006)

Kg/TJ			
Fuel	**Default**	**Lower**	**Upper**
Gasoline	69.300	67.500	73.000
Gas/Diesel Oil	74.100	72.600	74.800

For gases other than CO_2, very common Tier 1 default emission factors below Table 7 are provided.

Table 7: Default water-borne navigation CH_4 and N_2O emission factors (IPCC 2006)

	CH4 (kg/TJ)	**N2O (kg/TJ)**
Ocean-going Ships *	7 + 50%	2 +140% -40%
*Default values derived for diesel engines using heavy fuel oil. Source: Lloyd’s Register (1995) and EC (2002)		

3.2.2 Method of calculating air pollutant emissions

The method for calculating air pollutant emissions from fishing vessels, due to a lack of data specific to domestic fishing vessels, is referenced from the 'EMEP/EEA air pollutant emission inventory guidebook 2013' (EMEP/EEA, 2013). Similar to IPCC 2006, EMEP/EEA 2013 also provides three calculation methods, Tier 1 to Tier 3 below Figure 7. However, just as in the case of GHG emissions, Tier 1 was applied to calculate air pollutant emissions from fishing vessels.

The calculation formula is as follows (EMEP/EEA, 2013).

$$E_i = \sum_m (FC_m \times EF_{i,m})$$

Where:

E_i = emission of pollutant I in kilograms;
FC_m = mass of fuel type m sold in the country for navigation (tonnes)
$EF_{i,m}$ = fuel consumption-specific emission factor of pollutant I and fuel type m [kg/tonne];
m = fuel type (bunker fuel oil, marine diesel oil, marine gas oil, gasoline).

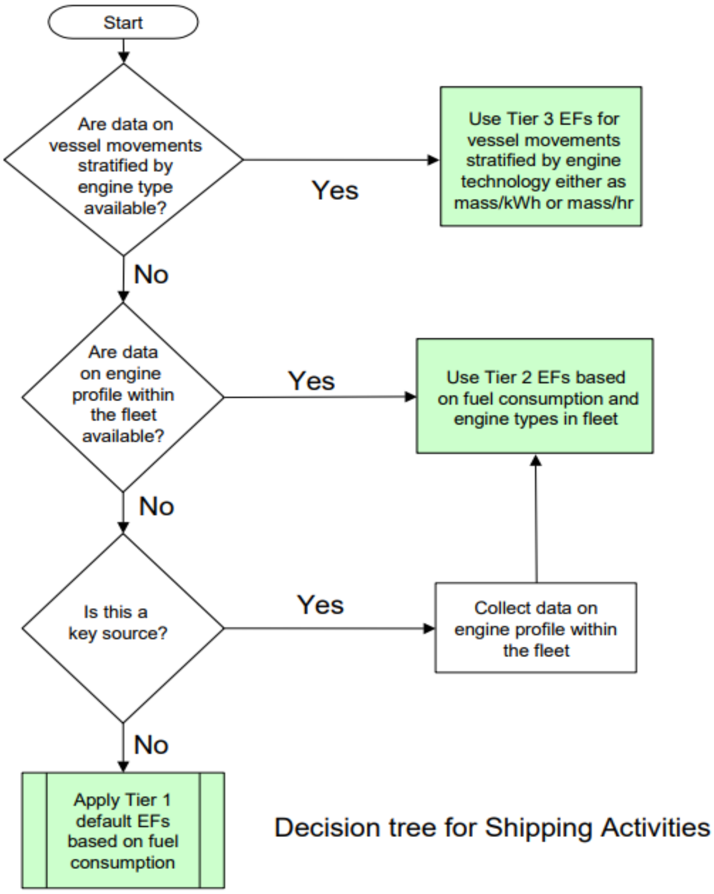


Figure 7: Decision tree for emissions from shipping activities (EMEP/EEA, 2013)

Emission factors, according to EMEP/EEA 2013, are as shown in Table 8. The sulfur content of SO_x is based on the 2015 data for different types of fuels, reflecting the sulfur content for each type of fuel, as presented in NIER (2018) (Table 9). However, in this study, the installation of EGTS for reducing air pollutants from vessels is only considered for Inboard-type diesel engines in fishing vessels with a gross tonnage of less than 10 tons; hence, only the emission factors for MDO/MGO are taken into account.

Table 8: Emission factors for ship emissions (EFi,m) (EMEP/EEA, 2013)

Fuel type	**CO**	**NOx**	**SOx**	**PM-10**	**PM-2.5**
Gasoline	573.9	9.4	20S*	9.5	9.5
MDO/MGO	7.4	78.5	20S*	1.5	1.4
BFO	7.4	78.5	20S*	6.2	5.6

Table 9: Sulfur content by fuel types (NIER, 2018)

Fuel type	Sulfur content (wt%)
Gasoline	0.00058
Diesel (0.05%)	0.03517
B-A (2.0%)	1.48500
B-B (3.0%)	3.00000

3.3 Method for estimating GHG and air pollutants from fishing vessels

3.3.1 Identifying fuel consumption without considering the route of the fishing vessel

Through the literature review in Chapter 2, it was observed that fishing vessels, unlike passenger and cargo ships, lack route information, which limits the calculation of emissions based on navigational characteristics and routes. Furthermore, in the domestic fishing vessel sector, data management, including routes and operational patterns, is challenging, resulting in limited detailed statistics on exhaust gas emissions.

However, information about GHG and air pollutant emissions from fishing vessels in Republic of Korea can be obtained from the Ministry of Environment and the Ministry of Oceans and Fisheries. While the overall GHG emissions for the country can be checked through the National GHG Management System provided by the GHG Inventory and Research Center (ME, 2023), the GHG emissions specific to fishing vessels based on fuel types and consumption were not available. Nevertheless, the direct emissions based on fishing vessel fuel usage were found in the 'Marine and Fisheries Sector 2050 Carbon Neutrality Roadmap,' published by the Ministry of Oceans and Fisheries in December 2021, which reported that the total GHG emissions from fishing vessels in 2018 amounted to 2.538 million tons (MOF, 2021).

As for air pollutant emissions, data regarding shipping vessel emissions of air pollutants can be obtained from the CAPSS of the NAEIR. These emission statistics are based on fuel consumption data categorized by regional associations of the National Federation of Fisheries Cooperatives, focusing on domestic coastal and offshore fishing vessels. Therefore, the emission quantities of air pollutants categorized by fuel type are available, as shown in Table 10.

Table 10: Emissions of air pollutants from fishing boats using diesel engines (NAEIR, 2023)

National Air Emission Inventory and Research Center	CAPSS (2020), unit: kg/year					
	CO	NO_x	SO_x	PM-10	PM-2.5	VOC
Diesel Engine	5,418,189	57,480,507	246,465	1,119,809	1,044,282	2,049,701
Gasoline Engine	41,046,820	672,320	885	679,459	679,459	12,981,341

<https://www.air.go.kr/article/view.do?boardId=10&articleId=294&boardId=10&menuId=32&currentPageNo=1>

In this manner, data on GHG emissions from Republic of Korean fishing vessels, as well as air pollutant emissions from fishing vessels using diesel oil, were obtained from the Republic of Korean Ministry of Environment and the Ministry of Oceans and Fisheries. However, as previously mentioned, obtaining route information for fishing vessels is exceptionally challenging. Therefore, it was not possible to determine GHG and air pollutant emissions from fishing vessels based on vessel size and engine power. Additionally, the statistical data for each emission differed based on the year. Consequently, in this study, assumptions were made based on the GHG emissions from fishing vessels reported by the Ministry of Oceans and Fisheries and the air pollutant emissions statistics from the NAEIR. These assumptions were supported by using engine power data from the KOMSA.

3.3.1.1 Assumption 1

It is assumed that the statistics for GHG emissions from fishing vessels in 2018 and the total emissions of air pollutants from fishing vessels in 2020 match the data from KOMSA's fishing vessel inspection records as of May 2023. According to the Marine Fisheries Statistics System, the total number of fishing vessels in Republic of Korea decreased by approximately 2.18% from 65,089 vessels in 2018 to 63,669 vessels in 2022. Therefore, as this decrease is relatively minor, it is assumed that the difference in GHG and air pollutant emissions from fishing vessels is also negligible.

3.3.1.2 Assumption 2

It was assumed that the power of fishing vessel engines is directly proportional to fuel consumption. Even for vessels under 10 tons, as shown in Figure 8, the vessel's tonnage and the engine's power are not directly proportional. Therefore, instead of tonnage, the engine's power was considered.

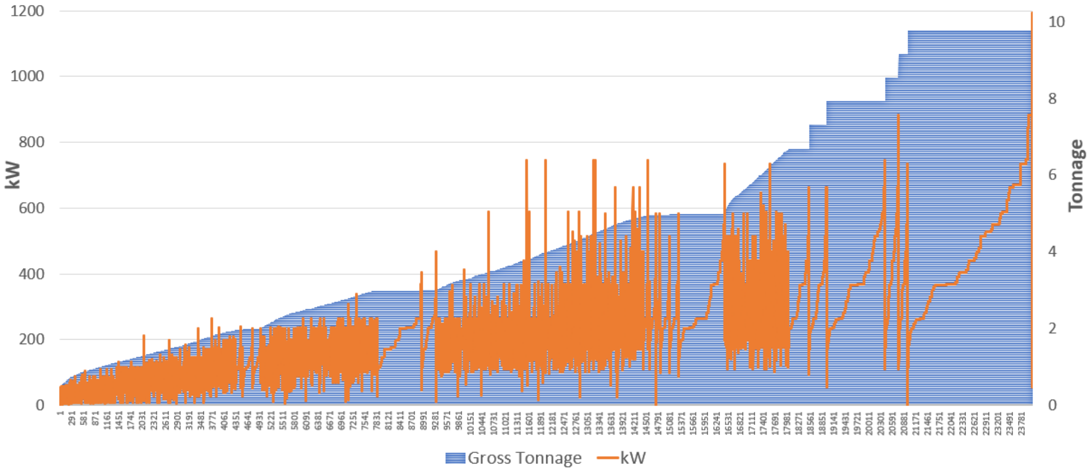


Figure 8: Relationship between ton class and power of small fishing boats under 10 tons

The power obtained from a given amount of fuel generally varies depending on engine type and operating conditions. The fuel consumption is typically proportional to engine output. The resistance (R) of a vessel is proportional to its speed and, when a vessel encounters resistance, the power required for the vessel to maintain a constant speed (P) is defined by the vessel's resistance (R) and speed (V), as shown in Equation (1).

$$P\ (kW) = R \times V \qquad (1)$$

Here, V represents the average speed of the vessel, and R is the sum of frictional resistance (FR), wave resistance (WR), eddy resistance (ER), and air resistance (AR) as expressed in Equation (2).

$$R\ (k\Omega) = frictional\ resistance\ (FR) + wave\ resistance\ (WR) + eddy\ resistance\ (ER) + air\ resistance\ (AR) \qquad (2)$$

Here, it can be observed that the power required for a vessel's navigation is proportional to its speed. Furthermore, engine output is proportional to speed, and engine output is also proportional to fuel consumption. Therefore, it can be concluded that there is a proportional relationship between speed and fuel consumption for fishing vessels with unknown routes (Maeda and Kim, 2013). Based on this, it was assumed that the fuel consumption of fishing vessels is proportional to kW in order to determine GHG and air pollutant emissions for fishing vessels with unknown routes.

3.3.2 Calculating factors to find fuel consumption

Having obtained GHG and air pollutant emissions data from fishing vessels in Chapter 3.3.1, it is possible to reverse-engineer the fuel consumption values required for these emissions. However, this data pertains to the entire fishing fleet, so to determine emissions by vessel size, it is necessary to know fuel consumption by engine power (kW) for each fishing vessel. Therefore, to align the emissions data with fuel consumption, specific factors were calculated for each type of exhaust gas. These factors, categorized by exhaust gas type, were determined to be the product of engine power (kW) and Factor for the given exhaust gas. To achieve this, engine power data for fishing vessels was classified by tonnage and engine type and summarized in Table 11.

Table 11: kW by fishing vessel tonnage and fuel type

Category		**Total**	**Gasoline (kW)**				**Diesel (kW)**			
			Sub total	**Inboard**	**Outboard**	**Stern drive**	**Sub total**	**Inboard**	**Outboard**	**Stern drive**
Sum of Main Engine Power (kW)	Total	**11,311,618**	**3,586,603**	3,554	3,567,793	15,256	**7,725,015**	7,670,014	4,299	50,703
	～1 ton	490,407	452,085	595	449,549	1,940	38,323	38,224	99	
	1～2 ton	2,142,188	1,791,640	2,312	1,781,181	8,147	350,549	345,020	1,192	4,337
	2～3 ton	1,288,889	629,461	463	626,117	2,881	659,427	653,164		6,263
	3～5 ton	2,296,841	513,854	-	512,633	1,221	1,782,987	1,761,307	327	21,353
	5～10 ton	3,172,383	195,245	184	194,547	515	2,977,137	2,958,082	2,137	16,919
	10～20 ton	473,671	4,318	-	3,767	551	469,353	468,066	368	919
	20～50 ton	739,716	0	-	-	-	739,716	738,627	176	912
	50 ton～	353,762	0	-	-	-	707,523	707,523		

3.3.2.1 Relationship between GHG emissions from fishing vessels and fuel consumption

Chapter 3.3.1 provides that the GHG emissions from fishing vessels in 2018 were 2.538 million tons, including CO_2, CH_4, and N_2O. Therefore, assuming the sum of kW for gasoline and diesel from Table 9 as fuel consumption, the ‘Fuel Consumed$_{ab}$’ was calculated using the Tier 1 equation from IPCC 2006 in Chapter 3.2.1. As a result, it was determined that Gas/Diesel Oil consumption accounted for approximately 69.09%, while Gasoline consumption accounted for approximately 30.91% of the total. Applying these ratios to the total GHG emissions yields Table 12 below. Fishing vessels using Diesel Oil were found to emit approximately 1,753,562 tons of GHG, while those using Gasoline emitted approximately 784,438 tons.

Table 12: GHG emissions by fuel type

GHG Inventory and Research Center	**GHG (ton/year)**	
MOF (2021.12)	2,538,000	
Gas/Diesel Oil	69.09 %	1,753,562
Gasoline	30.91 %	784,438

3.3.2.2 Relationship between air pollutant emissions from fishing vessels and fuel consumption

The emission of air pollutants from fishing vessels was confirmed based on the fuel-specific emission data for fishing vessels in 2020, as discussed in Chapter 3.3.1, obtained from CAPSS. However, as mentioned in Chapter 1.4, one of the objectives of this study related to air pollutants from fishing vessels is to install EGTS on small vessels, especially those under 10 tons, in order to reduce pollutant emissions. For this reason, it is necessary to separately estimate the emissions of air pollutants from diesel-powered fishing vessels with inboard engines under 10 tons. To achieve this, it is first necessary to calculate the total emissions of air pollutants for fishing vessels by fuel type and ensure they match the results obtained from CAPSS. Therefore, the sum of kW for gasoline and diesel, as identified in Table 11, and the product of the Factors mentioned in Chapter 3.3.2 were assumed to be the fuel consumption (FC_m). The total emissions of air pollutants by fuel type were then calculated using the Tier 1 formula from the EMEP/EEA 2013 guidelines in Chapter 3.2.2. As a result, the total emissions of air pollutants by fuel type, excluding SO_x, showed differences within 2%, as presented in the following Table 13. The difference in SO_x emissions is believed to be due to variations in sulfur content in the fuel.

Table 13: Deviation between CAPSS and assumption

	Diesel			**Gasoline**		
	CAPSS (2020)	**Match with CAPSS**	***Deviation (%)***	**CAPSS (2020)**	**Match with CAPSS**	***Deviation (%)***
CO	5,418,189	5,525,008	*1.97%*	41,046,821	41,043,525	*0.01%*
NOx	57,480,507	58,609,885	*1.96%*	672,320	672,258	*0.01%*
SOx	246,465	525,174	*113.08%*	885	830	*6.30%*
PM-10	1,119,809	1,119,934	*0.01%*	679,459	679,410	*0.01%*
PM-2.5	1,044,282	1,045,272	*0.09%*	679,459	679,410	*0.01%*
VOC	2,049,701	2,090,544	*1.99%*	12,981,341	12,980,310	*0.01%*

As shown in the above table, it can be observed that more air pollutants, excluding carbon monoxide, are generated by Diesel engines. Therefore, to categorize air pollutants generated specifically by Diesel engines by engine type and classify them into vessels with a total tonnage of less than 10 tons and those with a total tonnage of 10 tons or more, Figure 9 is presented.

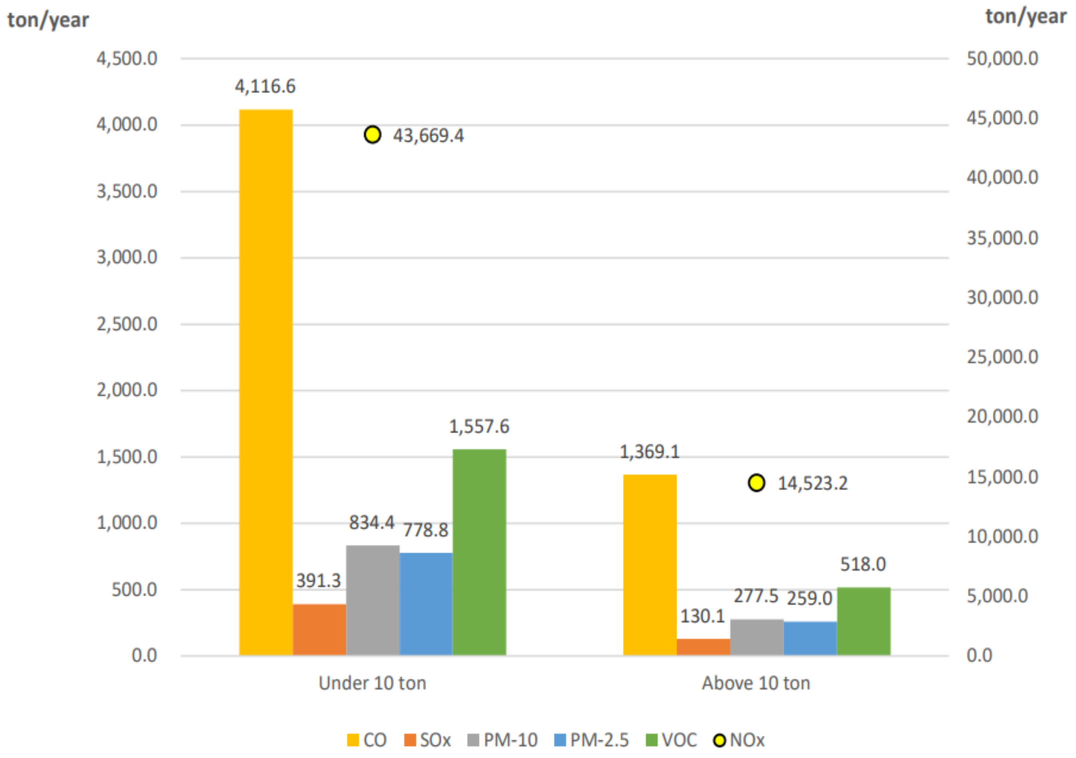


Figure 9: Comparison of Pollutant Emissions from Inboard Fishing Vessels Using Diesel Oil

As can be seen from the above graph, it can be observed that air pollutant emissions from small vessels under 10 tons are higher than those from vessels of 10 tons or more. Therefore, as one of the objectives of this study, in order to apply the EGTS to fishing vessels, it is decided to install this system on Inboard type Diesel propulsion engines that can be equipped on small vessels under 10 tons.

3.4 Methodology for Evaluating Suitable Alternative Fuels for Fishing Vessels

To identify the most suitable alternative for reducing GHG emissions in fishing vessels, the TOPSIS methodology was employed. (Hwang and Yoon, 1981) developed the TOPSIS methodology based on the intuitive principle that selected alternatives should be closest to the ideal positive solution and farthest from the ideal negative solution. TOPSIS is very effective in rapidly identifying the best alternative and involves the following steps. Firstly, calculate normalized ratings, then calculate weighted normalized ratings. Thirdly, identify the positive ideal solution and the negative ideal solution. Fourthly, calculate the separation measures, and fifthly, calculate the similarity to the positive ideal solution to rank and identify priorities.

To do this, batteries for electric propulsion were added to Table 4 in Chapter 2.5.3.2 and expressed numerically. Green is represented as 1, orange as 2, and red as 3. For batteries, the Environment and operating expenditure (OPEX) were set to 1, while capital expenditure (CAPEX), Technological Maturity, Shipping, and Future Outlook were set to 3 in Table 14.

Table 14: Added Batteries based on the table 2 (Bilgili, 2023).

Attributes	**Environment**			**Cost**			**Technical**			**Social**		**Other**
	Emissions	**LCA**	**Health**	**Production**	**CAPEX**	**OPEX**	**Infrastructure**	**Technological Maturity**	**Shipping**	**Safety**	**Legislations**	**Future Outlook**
Ammonia	2	2	3	3	3	3	3	1	1	3	2	3
Biodiesels	1	1	1	2	2	2	2	3	1	3	2	3
DME	1	N/A	1	N/A	3	1	N/A	1	1	3	2	2
Ethanol	1	2	1	N/A	2	3	N/A	1	1	1	2	2
Hydrogen	1	2	1	3	3	3	1	1	1	1	2	3
LNG	1	2	1	2	3	1	2	3	2	2	2	2

LPG	1	2	2	N/A	3	2	3	1	1	2	2	N/A
Methanol	1	2	3	3	1	2	3	3	2	1	2	2
Batteries	1	2	2	2	3	1	2	3	3	2	2	3

Firstly, the calculation of normalized scores, as given in equation (1), results in the values shown in Table 15.

$$r_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^{m} x_{ij}^2}} \qquad (1)$$

Table 15: Added Batteries based on the table 2 (Bilgili, 2023) and calculated of normalized scores

Attributes	Environment			Cost			Technical			Social		Other
	Emi-ssions	**LCA**	**Health**	**Pro-duction**	**CAPEX**	**OPEX**	**Infra-structure**	**Techno-logical Maturity**	**Shi-pping**	**Safety**	**Legi-slations**	**Future Outlook**
Ammonia	0.577	0.371	0.539	0.480	0.378	0.463	0.474	0.156	0.209	0.463	0.333	0.416
Biodiesels	0.289	0.186	0.180	0.320	0.252	0.309	0.316	0.469	0.209	0.463	0.333	0.416
DME	0.289	0.000	0.180	N/A	0.378	0.154	N/A	0.156	0.209	0.463	0.333	0.277
Ethanol	0.289	0.371	0.180	N/A	0.252	0.463	N/A	0.156	0.209	0.154	0.333	0.277
Hydrogen	0.289	0.371	0.180	0.480	0.378	0.463	0.158	0.156	0.209	0.154	0.333	0.416
LNG	0.289	0.371	0.180	0.320	0.378	0.154	0.316	0.469	0.417	0.309	0.333	0.277
LPG	0.289	0.371	0.359	N/A	0.378	0.309	0.474	0.156	0.209	0.309	0.333	N/A
Methanol	0.289	0.371	0.539	0.480	0.126	0.309	0.474	0.469	0.417	0.154	0.333	0.277
Batteries	0.289	0.371	0.359	0.320	0.378	0.154	0.316	0.469	0.626	0.309	0.333	0.416

Secondly, weighted normalized ratings were all set to 1, and no separate calculation was performed.

Thirdly, positive ideal solutions and negative ideal solutions were identified as shown in Equations (2) and (3) below, and presented in Table 16. Environment and Cost have Ideal best as the minimum value, while Ideal worst is the maximum value. In contrast, Technical, Social, and Other have Ideal best as the maximum value, and Ideal worst as the minimum value.

$$A^* = \{v_1{}^*, v_2{}^*, \ldots, v_j{}^*, \ldots, v_n{}^*\}, \qquad (2)$$

$$where \;\; v_j{}^* = \{\max v_{ij}, j \in j_1;\; \min v_{ij}, j \in j_2\}$$

$$A^- = \{v_1{}^-, v_2{}^-, \ldots, v_j{}^-, \ldots, v_n{}^-\}, \qquad (3)$$

$$where\ \ v_j{}^- = \{\min v_{ij}, j \in j_1;\ \max v_{ij}, j \in j_2\}$$

Table 16: Added Batteries based on the table 2 (Bilgili, 2023) and calculated positive ideal solutions and negative ideal solutions

Attributes	Environment			Cost			Technical			Social		Other
	Emissions	LCA	Health	Production	CAPEX	OPEX	Infrastructure	Technological Maturity	Shipping	Safety	Legislations	Future Outlook
Ammonia	0.577	0.371	0.539	0.480	0.378	0.463	0.474	0.156	0.209	0.463	0.333	0.416
Biodiesels	0.289	0.186	0.180	0.320	0.252	0.309	0.316	0.469	0.209	0.463	0.333	0.416
DME	0.289	N/A	0.180	N/A	0.378	0.154	N/A	0.156	0.209	0.463	0.333	0.277
Ethanol	0.289	0.371	0.180	N/A	0.252	0.463	N/A	0.156	0.209	0.154	0.333	0.277
Hydrogen	0.289	0.371	0.180	0.480	0.378	0.463	0.158	0.156	0.209	0.154	0.333	0.416
LNG	0.289	0.371	0.180	0.320	0.378	0.154	0.316	0.469	0.417	0.309	0.333	0.277
LPG	0.289	0.371	0.359	N/A	0.378	0.309	0.474	0.156	0.209	0.309	0.333	N/A
Methanol	0.289	0.371	0.539	0.480	0.126	0.309	0.474	0.469	0.417	0.154	0.333	0.277
Batteries	0.289	0.371	0.359	0.320	0.378	0.154	0.316	0.469	0.626	0.309	0.333	0.416
Ideal best(v_j^*)	0.289	0.186	0.180	0.320	0.126	0.154	0.474	0.469	0.626	0.463	0.333	0.416
Ideal worst(v_j^-)	0.577	0.371	0.539	0.480	0.378	0.463	0.158	0.156	0.209	0.154	0.333	0.277

Fourthly, separation measures for each column are calculated. The separation (distance) between alternatives can be measured using n-dimensional Euclidean distance. The separation of each alternative from the positive ideal solution is given by Equations (4) and (5) below and presented in Table 17.

$$S_i{}^* = \sqrt{\sum_{j=1}^{n}(v_{ij} - v_j{}^*)^2} \qquad \text{i = 1, 2, …, m} \qquad (4)$$

$$S_i{}^- = \sqrt{\sum_{j=1}^{n}(v_{ij} - v_j{}^-)^2} \qquad \text{i = 1, 2, …, m} \qquad (5)$$

Table 17: Added Batteries based on the table 2 (Bilgili, 2023) and calculated separation measures for each column

Attributes	Environment			Cost			Technical			Social		Other	S_i*	S_i^-
	Emissions	LCA	Health	Production	CAPEX	OPEX	Infrastructure	Technological Maturity	Shipping	Safety	Legislations	Future Outlook		
Ammonia	0.577	0.371	0.539	0.480	0.378	0.463	0.474	0.156	0.209	0.463	0.333	0.416	0.838	0.463
Biodiesels	0.289	0.186	0.180	0.320	0.252	0.309	0.316	0.469	0.209	0.463	0.333	0.416	0.488	0.741
DME	0.289	N/A	0.180	N/A	0.378	0.154	N/A	0.156	0.209	0.463	0.333	0.277	0.846	0.892
Ethanol	0.289	0.371	0.180	N/A	0.252	0.463	N/A	0.156	0.209	0.154	0.333	0.277	0.927	0.696
Hydrogen	0.289	0.371	0.180	0.480	0.378	0.463	0.158	0.156	0.209	0.154	0.333	0.416	0.828	0.481
LNG	0.289	0.371	0.180	0.320	0.378	0.154	0.316	0.469	0.417	0.309	0.333	0.277	0.458	0.723
LPG	0.289	0.371	0.359	N/A	0.378	0.309	0.474	0.156	0.209	0.309	0.333	N/A	0.851	0.756
Methanol	0.289	0.371	0.539	0.480	0.126	0.309	0.474	0.469	0.417	0.154	0.333	0.277	0.609	0.642

Batteries	0.289	0.371	0.359	0.320	0.378	0.154	0.316	0.469	0.626	0.309	0.333	0.416	0.423	0.759
Ideal best(v_j^*)	0.289	0.186	0.180	0.320	0.126	0.154	0.474	0.469	0.626	0.463	0.333	0.416		
Ideal worst(v_j^-)	0.577	0.371	0.539	0.480	0.378	0.463	0.158	0.156	0.209	0.154	0.333	0.277		

Fifthly, the similarity to the positive ideal solution is calculated as shown in Equation (6) below. If C_i^* is close to 1, the alternative is considered ideal, and if close to 0, it is considered non-ideal.

$$C_i^* = \frac{S_i^-}{S_i^* + S_i^-}, \ 0 < C_i^* < 1; \ i=1, 2, \ldots, m \qquad (6)$$

By ranking the values of C_i^* in descending order, it can be seen that Batteries are ranked first in Table 18.

Table 18: Added Batteries based on the table 2 (Bilgili, 2023) and ranked

Attributes	Si+	Si-	Si+ + Si-	Ci	Rank
Ammonia	0.838	0.463	1.301	0.356	9
Biodiesels	0.488	0.741	1.230	0.603	3
DME	0.846	0.892	1.739	0.513	4
Ethanol	0.927	0.696	1.623	0.429	7
Hydrogen	0.828	0.481	1.309	0.368	8
LNG	0.458	0.723	1.181	0.612	2
LPG	0.851	0.756	1.607	0.470	6
Methanol	0.609	0.642	1.251	0.513	5
Batteries	0.423	0.759	1.182	0.642	1

Chapter 4. Technical Review

In this chapter, the technical specifications that need to be considered for the building of electric propulsion fishing vessels, which are suitable alternative fuels for GHG reduction using the TOPSIS methodology as discussed in Chapter 3.4, are reviewed. Additionally, a technical approach is taken for EGTS to reduce air pollution from existing small vessels.

4.1. Considerations for the building of electrically propelled fishing vessels

To build electric propulsion fishing vessels, it is necessary to develop key technologies for highly efficient and cost-effective electric propulsion vessels optimized for fishing vessels, as well as to develop practical technologies for testing and applying them. From this perspective, three aspects for developing electric propulsion fishing vessels was examined.

4.1.1 Development of core equipment and charging infrastructure

The production of essential components for electric powertrains, charging equipment, and control technology is required. Additionally, the development of the upper-level control system for powertrain, utilizing the existing power distribution system for efficient power distribution, is necessary. Therefore, the first item derived for the technical development of electric propulsion vessels is the development of key components and charging infrastructure technology. The details are as follows.

- Design and production of core components for electrically propelled fishing vessels.

- Development of upper-level control systems that can utilize the existing power system efficiently.
- Development of real-time monitoring systems for power systems.
- Development of charging infrastructure technology for electrically propelled fishing vessels.
- Establishment of testing equipment and related facilities for electric powertrains.

Detailed development activities related to this are as follows:

4.1.1.1 Optimal design of electric motor for electric propulsion fishing boat through analysis of operation information of existing fishing boat

- Conduct a cluster analysis of the operating characteristics of existing fishing vessels and select representative operating cycles based on the clusters.
- Analyze the representative operating cycles to define suitable operational conditions (operating distance, speed, etc.).
- Operate using the main engines of existing fishing vessels for various load conditions based on the tonnage of the vessels.
- Determine the key specifications (rated torque, maximum rotational speed, etc.) for the electric motors required for electrically propelled fishing vessels based on the suitable operating information for each vessel.
- Optimal design of the electric motor is necessary based on the determined key specifications. Applying optimal design to the electric motor requires interdisciplinary knowledge and experience, including electrical circuits, electromagnetic field analysis, and optimal design theory.
- For the type of electric motor, options such as Interior Permanent Magnet (IPM), Surface Permanent Magnet (SPM) synchronous motors, Reluctance motors (SRM), Induction motors (IM), and Synchronous Reluctance motors (SynRM) can be selected based on factors like size, high power output, and a wide operating range, as shown in Table 19 below.

Table 19: Electric Motor Types and Features (Chae, 2013)

	SPM	**IPM**	**SynRM**	**SRM**	**IM**
Structure					
Efficiency	Very good	Very good	Fair	Fair	Poor
RPM	Fair	Very good	Good	Very good	Good
High Torque	Very good	Very good	Good	Very good	Poor
Cost	Poor	Fair	Very good	Very good	Very good
Torque Ripple	Very good	Good	Good	Poor	Very good

4.1.1.2 Development of controller design and optimization algorithm required for synchronization of engine power and electric motor power

- In traditional fishing vessels, propulsion engines are often operated in a high load, low-efficiency mode to reduce transit time to fishing grounds. This practice can lead to reduced engine efficiency.
- The optimal operating points for engines and electric motors differ. To increase efficiency when designing electric propulsion systems, it is essential to find the optimal operating point that considers both the engine and the motor.

4.1.1.3 Development of real-time battery monitoring system and battery management system for safe and efficient use of batteries

- High-energy-density lithium-ion batteries are often used by connecting multiple battery cells in series to obtain the required capacity. Inevitably, differences between battery cells arise due to chemical properties, manufacturing processes, storage conditions, etc. These differences can negatively affect overall efficiency by causing the battery pack (a collection of all battery cells) to overheat or deteriorate rapidly, significantly reducing its lifespan. Therefore, the development of a battery management system is necessary to monitor the physical phenomena exhibited by each cell and balance all cells for optimal battery performance.

- Additionally, lithium-ion batteries, due to their high energy density, pose a risk of ignition or explosion during overcharging or over-discharging. To ensure safety and reliability, an integrated monitoring system that observes battery temperature and hazardous conditions is required.

4.1.1.4 Establishment of charging infrastructure for efficient power supply to electric propulsion fishing boats

- A power test system is required to evaluate the performance of core components for electric propulsion fishing boats, including electric motors, battery packs, controllers, integrated monitoring systems, and more.
- It is necessary to test the power of the entire fishing vessel and assess aspects such as durability, exhaust emissions, vibrations, noise, etc., requiring a chassis dynamometer.
- The establishment of a demonstration center for retrofitting and performance testing on both land and sea is essential. Specifically, the construction of high-current/high-voltage safety equipment is mandatory for testing large-capacity electric propulsion systems.

4.1.1.5 Establishment of charging infrastructure for efficient power supply to electric propulsion fishing boats

- Charging infrastructure refers to tangible and intangible facilities, equipment, and software involved in the process of supplying electricity.
- To ensure efficient and stable power supply to fishing vessels on land and at sea, the development of charging infrastructure is necessary.
- Similar to the increase in the adoption of electric vehicles with the expansion of charging infrastructure, charging facilities are needed for the widespread adoption of electric propulsion fishing boats.

4.1.2 Standard hull design for electrically propelled fishing boats

When an electric powertrain is to be installed on a fishing vessel, the construction of a new hull or modification of an existing one is required, necessitating analyses of reliability and stability, among other aspects. Therefore, the standard hull design for electric propulsion fishing vessels and related technology development were identified as the second task, with detailed specifics as follows:

- Gathering operational data from existing fishing vessels to derive specifications for key components of the electric propulsion system.
- Determining the optimal arrangement of each key component and the powertrain within the vessel, based on the derived specifications.
- Analyzing the stability and structural reliability of the standard hull.

Hence, the key technological development aspects related to this are as follows:

- Reflecting design requirements according to the characteristics of electric propulsion fishing boats
- Basic design of electric propulsion fishing boat based on design
- Based on the basic design results, detailed design such as layout for structure, shape, dimensions, and arrangement for actual shipbuilding

4.1.3 Technology development and system establishment for verification and commercialization of electrically propelled fishing boats

To enable the practical application of electric propulsion fishing boats following their development, it is necessary to establish a testbed, conduct practical demonstrations, and evaluate the performance of these boats for approval. Furthermore, to certify and disseminate the developed technology, revisions to laws and regulations are also required. Therefore, to derive the development of technology and the establishment of a system for the verification and practical use of electric propulsion fishing boats, the following specific tasks can be performed:

- Conduct performance evaluations and certification of key components for electric propulsion fishing boats.
- Review certification regulations for structural modifications of electric propulsion fishing boat hulls.

- Undertake the construction of electric propulsion fishing boat hulls.
- Establish maintenance guidelines for electric propulsion fishing boat hulls.
- Establish a testbed and conduct practical demonstrations of electric propulsion fishing boats.
- Develop legal and regulatory mechanisms for the dissemination of electric propulsion fishing boats.

Therefore, the key content of technology development related to these matters is as follows.

- Derivation of performance evaluation criteria and methods for evaluating whether electrically propelled fishing boats reach the low-emission target level, and structural change approval plan for manufacturing and remodeling fishing boats
- Select a test route and derive an operation plan to measure the effect of the fishing boat to which the developed technology is tested, and calculate the applicability and effect of the electric hybrid propulsion fishing boat technology
- Develop business models such as market distribution cost determination, publicity and distribution strategies, etc. for effective dissemination of electric combined propulsion fishing boat technology, and review existing laws and systems utilization plans and institutional obstacles resolution plans for smooth commercialization

4.2. Technologies for reducing air pollutants emissions from fishing boats

The ship EGTS refers to a system that removes or reduces harmful exhaust gases generated during the combustion process of a ship, as shown in the figure below. Such systems play a crucial role in environmental protection and human health, primarily serving as devices to reduce atmospheric pollutants such as particulate matter, NO_x, and SO_x.

There are various types of EGTS, but this study introduces an EGTS patented by the KOMSA, which is suitable for installation on small vessels. This system is designed to maximize space efficiency by effectively configuring the exhaust gas treatment components, as shown in the Figure 10 below, especially in small vessels where space for mandatory exhaust gas purification equipment installation is limited, in accordance with strengthening regulations for marine environmental pollution control (Seong et al., 2022).

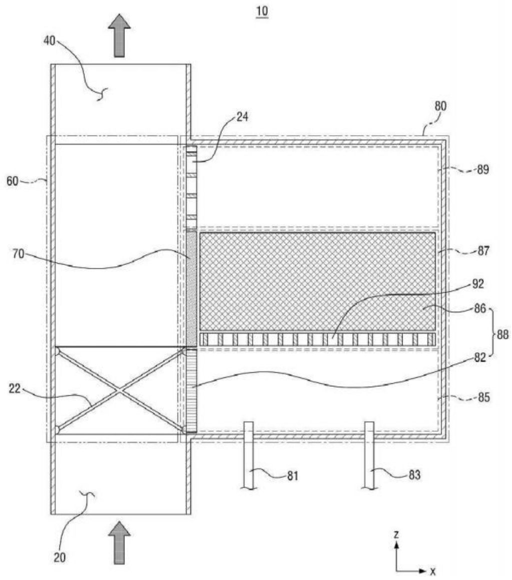


Figure 10: Patent EGTS for small vessels (Seong et al., 2022)

As shown in the Figure 11 below, the diverter damper operates according to the control signal, allowing gases to flow selectively through two types of ducts. In this way, in the case of small vessels, the bypass integrated system can effectively reduce the space required for the EGTS installation while efficiently removing pollutants. Additionally, it can simultaneously handle fine PM and nitrogen oxides, incorporating Diesel Oxidation Catalyst (DOC) and Selective Catalytic Reduction Filter (SCRF) catalysts. The DOC catalyst can purify CO, Hydrocarbons (HC), Soluble Organic Fraction (SOF), and oxidize them into NO and NO_2 through oxidation catalytic reactions. The SCRF catalyst includes a reducing agent injection device in the previous stage, such as UREA injection. For example, when navigating in emission control areas specified by law, it can perform NO_x removal by injecting reducing agents in addition to PM removal. When navigating outside emission control areas, it can perform only PM removal. In other words, by selectively removing target substances, it is possible to satisfy emission regulations while achieving effective pollution removal, prolonging system life, and maintaining the temperature at a certain level for the disintegration of reducing agents and PM regeneration using a burner (Seong et al., 2022).

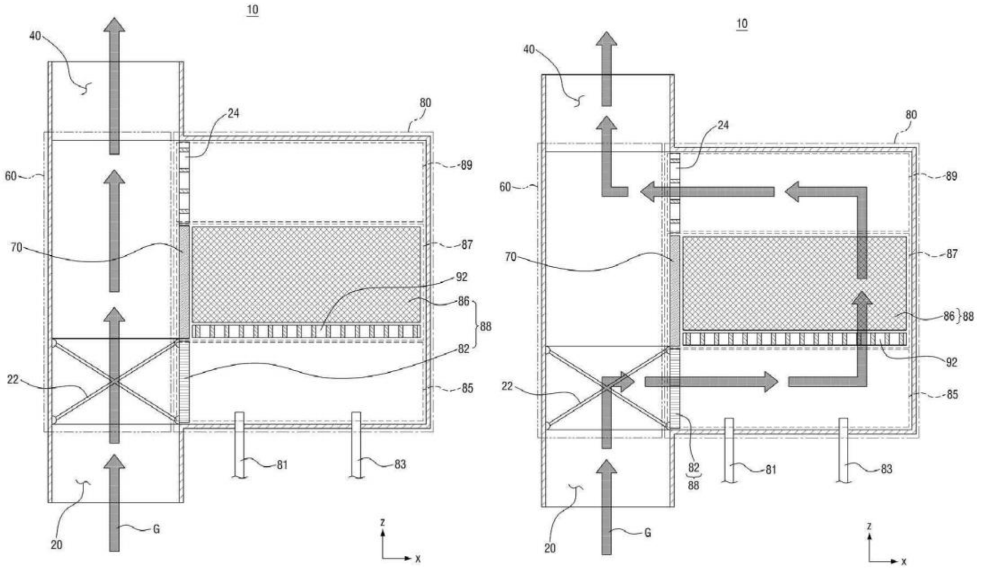


Figure 11: Composition of the effective flow path (Seong et al., 2022)

Chapter 5. Concept Design

In this chapter, the required space for battery installation when applying a purely electric propulsion system is examined by considering the major dimensions, operating time, and fishing time of the current coastal and offshore fishing vessels. Subsequently, a conceptual general arrangement drawing is created. Next, a conceptual general arrangement drawing for installing a EGTS on small fishing vessels is developed, and the impact on each is evaluated.

5.1. Electric Fishing vessel

In order to determine the battery capacity and weight of electric propulsion vessels, it is necessary to consider not only the vessel's propulsion power, speed, navigation, and fishing time but also the energy based on battery volume and weight. Here, considering LI-ion batteries, the expected volumetric energy density of the battery (kWh/m^3) ranges from 200 to 500 kW/m^3 (Chen et al., 2009; Perčić et al., 2022; Xue et al., 2017). Furthermore, the gravimetric energy density of the battery (kWh/ton) also ranges from 75 to 200 kW/ton.

As in the previous Chapter 3, the average data for vessel dimensions, including Length (L), Breadth (B), and Depth (D), were categorized to calculate the average key dimensions and are presented in Table 20.

Table 20: Main Fish category

Category			**Coastal Fishing Vessel (ton)**					**Offshore Fishing Vessel (ton)**		
		(m)	**~ 1**	**1 ~ 2**	**2 ~ 3**	**3 ~ 5**	**5 ~ 10**	**10 ~ 20**	**20 ~ 50**	**50 ~**
Average (m)		L	5.41	7.00	8.26	9.43	12.59	16.24	22.14	32.42
		B	1.70	2.14	2.42	3.27	4.23	5.34	5.08	6.48
		D	0.58	0.75	0.78	0.82	0.85	0.93	1.78	2.72
Gasoline (m)	Inboard	L	5.36	6.66	8.39	-	11.79	-	-	-
		B	1.74	2.18	2.29	-	5.00	-	-	-
		D	0.58	0.78	0.67	-	0.79	-	-	-
	Outboard	L	5.42	6.72	8.10	9.14	12.00	16.03	-	-
		B	1.77	2.07	2.50	3.13	4.72	5.64	-	-
		D	0.63	0.79	0.82	0.83	0.76	0.96	-	-
	Stern drive	L	4.78	6.99	8.22	9.13	12.76	-	-	-
		B	1.62	2.12	2.44	3.64	5.15	-	-	-
		D	0.53	0.81	0.89	0.95	0.68	-	-	-
Diesel (m)	Inboard	L	6.37	7.39	8.43	9.84	13.57	16.80	21.65	32.42
		B	1.82	2.15	2.59	3.07	3.85	4.90	5.06	6.48
		D	0.54	0.65	0.73	0.84	0.94	1.10	1.67	2.72
	Outboard	L	5.13	6.91	-	9.99	13.36	16.17	18.53	-
		B	1.55	2.07	-	3.75	3.50	5.42	4.50	-
		D	0.62	0.73	-	0.72	0.99	0.79	1.90	-
	Stern drive	L	-	7.30	8.17	9.03	12.06	15.95	26.25	-
		B	-	2.27	2.28	2.75	3.14	5.41	5.67	-
		D	-	0.73	0.80	0.78	0.94	0.86	1.78	-

Furthermore, coastal and offshore fishing vessels were classified, and their fishing days, fishing hours, and engine loads are presented in the following Table 21.

Table 21: Fisheries Survey Results (NIER, 2015)

	Number of working days per year	**Daily working hours (hours/day)**		**Annual working hours (hours/year)**		**Engine load factor (%)**	
	(day/year)	**Sail**	**Work**	**Sail**	**Work**	**Sail**	**Work**
Coastal Fishing	178	2	6	342	1148	79	19
Offshore Fishing	240	9	39	340	2442	73	20

5.1.1 Coastal Fishing vessels

Coastal vessels, which mainly operate for one day with equipment that can support their operations, are typically less than 10 tons in total tonnage. They usually operate within a range that allows them to return on the same day, with an actual range of about 20 nautical miles (NM) (approximately 40 km) being recognized. Figure 12 illustrates an example of a 5.49 ton coastal vessel.

Figure 12: Example of Coastal Fishing Vessel (NIFS, 2017)

Assuming that the vessels are built with specifications similar to those currently in operation along the coastal areas, the data of vessels, which are subjects of the stability calculation, were calculated, as shown in Table 22 and Table 23, to estimate the required capacity and weight of batteries. In Republic of Korea, vessels subject to stability calculations have a length of 24 meters or more or accommodate 13 or more passengers.

Table 22: Stability calculation data for 3 ~ 4.99 ton coastal fishing boats

Number	**Tonnage (Ton)**	**Lightweight (Ton)**	**Displacement (Ton)**	**Maximum Fuel Oil (Ton)**	**Engine Power (kW)**
1	3.00	8.085	12.974	0.625	235.2
2	3.00	8.214	15.739	2.758	235.2
3	3.25	6.784	12.092	0.744	232.3
4	4.82	11.008	15.757	1.759	235.2
5	4.79	8.229	14.380	0.930	235.2
6	4.99	12.228	17.375	1.587	264.6
Average	3.98	9.091	14.720	**1.401**	239.61

Table 23: Stability calculation data for 5 ~ 9.99 ton coastal fishing boats

Number	**Tonnage**	**Lightweight**	**Displacement**	**Maximum Fuel Oil**	**Engine Power**	
	(Ton)	**(Ton)**	**(Ton)**	**(Ton)**	**(PS)**	**(kW)**
1	7.93	18.854	26.145	3.783	600	441.0
2	9.77	22.642	40.165	13.379	550	404.3
3	9.77	28.297	45.167	3.329	550	404.3
4	6.52	13.158	23.670	2.72	500	367.5
5	6.67	13.314	17.414	0.981	500	367.5
6	7.93	11.262	15.649	1.137	600	441.0
7	5.47	12.088	18.020	3.272	545	400.6
8	5.11	13.000	24.420	1.7	500	367.5
9	8.55	17.647	32.964	2.831	600	441.0
10	8.55	13.890	19.483	1.863	600	441.0
Average	7.63	16.42	26.31	**3.50**	554.50	407.56

The average maximum fuel weight for vessels in the 3~5 ton category is approximately 1.4 tons, while for vessels in the 5~10 ton category, it is approximately 3.5 tons. This fuel weight represents the weight of fuel when vessels depart with a 98% load, considering only the energy required for propulsion and operation. Therefore, it appears that this fuel weight can be compared to the battery of an electric propulsion vessel without considering other factors.

On the other hand, since coastal vessels typically cover a distance of 20 NM in one day, and the operating time is set at 2 hours per day according to Table o, the vessel's cruising speed can be calculated as follows (Equation 1):

$$20\ NM \div 2\ hours \tag{1}$$

Here, the cruising speed can be considered approximately 10 knots. With an engine load of 79% during navigation, it can be inferred that the maximum speed is approximately 12.66 knots.

The required energy during navigation (in kWh) can be calculated using Equation 2:

$$Engine\ Power\ (kW) \times Navigation\ Time\ (hours) \times Engine\ Load\ (\%) \tag{2}$$

Additionally, the energy required during fishing operations (in kWh) can be calculated using Equation 3:

$$Engine\ Power\ (kW) \times Operating\ Time\ (hours) \times Engine\ Load\ (\%) \tag{3}$$

Therefore, the expected battery volume (in m^3) can be calculated using Equation 4:

Energy required during navigation and operation (kWh) ÷ Volumetric energy density (KWh/m^3*)* (4)

Similarly, the expected battery weight (in tons) can be calculated using Equation 5:

Energy required (kWh) ÷ Gravimetric energy density (KWh/ton) (5)

Based on the aforementioned operational information, the calculated amount of required energy is presented in the following Table 24.

Table 24: Energy requirements for existing coastal fishing vessels

Category		Average Propulsion Power	Maximum Speed	Engine load factor		Sailing	Daily working hours		Sailing Distance	Amount of required energy	
Type	Tonnage			Sail	Work	Speed	Sail	Work		Sail	Work
	(ton)	(kW)	(Knots)	(%)		(hours)	(hours)		(NM)	(kWh)	
Coastal Fishing Vessels	3～5	250	12.66	79%	19%	10	2	6	20.00	395	285
	5～10	400	12.66	79%	19%	10	2	6	20.00	632	456

When aligning the weight of fuel oil from Table 22 and Table 23 with the energy density of LI-ion batteries for vessels currently in operation, the result is as shown in Table 25. For the 3~5 ton category, in order to satisfy the 1.4 m^3 volume requirement, a battery with a volumetric energy density of 500 kW/m^3 must be applied, and to satisfy the 3.4 ton weight requirement, a gravimetric energy density of 200 kW/ton must be applied, even though it exceeds the weight by 109% compared to the existing setup.

For the 5~10 ton category, in order to satisfy the 3.5 m^3 volume requirement, a battery with a volumetric energy density of 310 kW/m^3 must be applied, and to satisfy the 4.07 ton weight requirement, a gravimetric energy density of 200 kW/ton must be applied, even though it exceeds the weight by 34% compared to the existing setup.

Table 25: Required energy density of existing coastal fishing vessels

Category		Maximum Fuel Oil		Energy density		Required Energy density	
Type	Tonnage	Volume	Weight	Volume	Weight	Volume	Weight
	(ton)	(m^3)	(ton)	(m^3)	(ton)	kWh/m^3	kW/ton
Coastal Fishing Vessels	3～5	1.4	1.63	1.4	3.4	500	200
	5～10	3.5	4.07	3.5	5.4	310	200

The Energy Density was calculated by varying the engine load and duration of engine operation for fixed average engine propulsion power, maximum speed, and navigation distance using ‘Crystal Ball’ to determine the maximum and minimum values. The results are shown in Table 26.

Table 26: Calculation of Energy density

Category			Average Propulsion Power	Maximum Speed	Engine load factor		(1) Sailing	Daily working hours		Sailing Distance	Amount of required energy		Energy density	
Type	Tonnage				Sail	Work	Speed	Sail	Work		(2) Sail	(3) Work	(4) Volume	(5) Weight
	(ton)		(kW)	(Knots)	(%)		(knots)	(hours)		(NM)	(kWh)		(m^3)	(ton)
Coastal Fishing Vessels	3~5	Min.	250	12.66	71%	17%	8.99	1.8	5.4	20.00	319.5	229.5	1.1	2.7
		Max.			87%	21%	11.01	2.2	6.6		478.5	346.5	4.1	11.0
	5~10	Min.	400	12.66	71%	17%	8.99	1.8	5.4	20.00	511.2	367.2	1.8	4.4
		Max.			87%	21%	11.01	2.2	6.6		765.6	554.4	6.6	17.6

For vessels with tonnages between 3 to 5 tons, energy consumption is generally about 10% lower than the average load, assuming the use of batteries with high energy density. In such cases, the batteries were occupied approximately 1.1 m^3 in volume and weigh 2.7 tons. Conversely, with 10% higher energy consumption and the use of batteries with lower energy density, the volume could increase to 4.1 m^3, and the weight to 11.1 tons.

Similarly, for vessels with tonnages between 5 to 10 tons, the volume can range from 1.8 to 6.6 m^3, and the weight from 4.4 to 17.6 tons, depending on energy consumption and the choice of batteries.

In summary, even if electric propulsion vessels have approximately 10% lower performance than traditional vessels, the batteries' weight must increase to meet the same energy requirements.

Therefore, considering battery capacity, a rough concept General Arrangement for electrically powered vessels is proposed here, as illustrated in Figure 13.

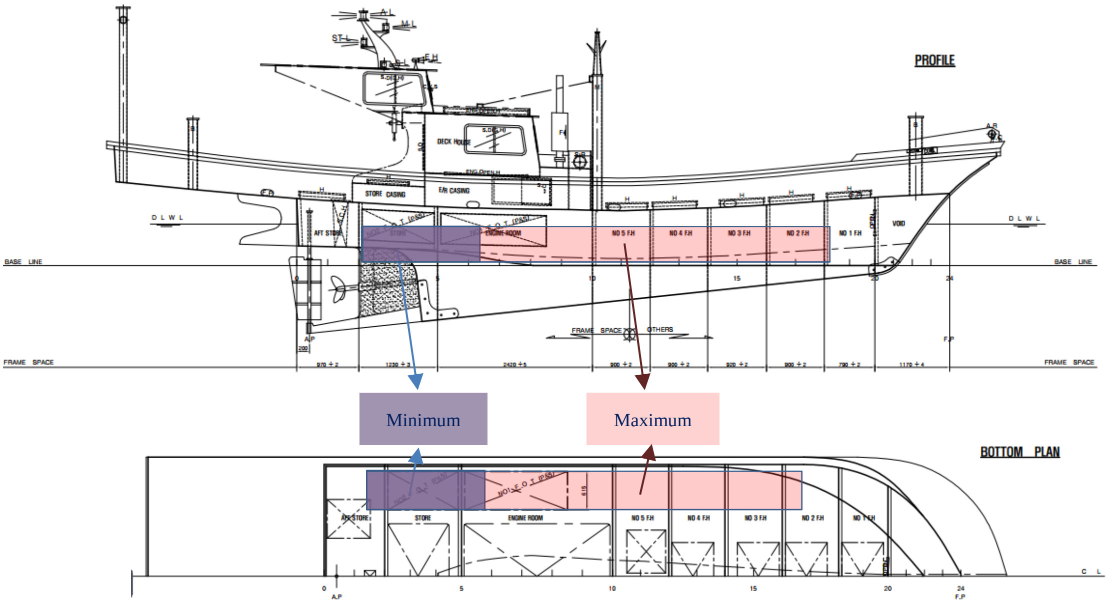


Figure 13: Concept Battery Arrangement for coastal fishing vessels

The minimum and maximum battery capacities are presented in the following Table 27.

Table 27: Volume of Batteries for Stability calculation data for 5 ~ 9.99 ton coastal fishing boats

Tonn -age	Minimum				Maximum			
	L	B	D	Vol.	L	B	D	Vol.
	(m)	(m)	(m)	(m^3)	(m)	(m)	(m)	(m^3)
4	1.83	0.6	0.5	0.55 x 2 = 1.10	6.83	0.6	0.5	2.05 x 2 = 4.10
7	1.67	0.9	0.6	0.90 x 2 = 1.80	6.11	0.9	0.6	3.30 x 2 = 6.60

5.1.2. Offshore Fishing vessels

Offshore fishing vessels typically operate for more than a day, usually 2-3 days, and most of them have a total tonnage of over 10 tons. Therefore, the navigation distance is typically about 100 Nautical Miles. The following Figure 14, 15 and 16 show examples of offshore fishing vessels of 20, 40 tons, and 140 tons, respectively.

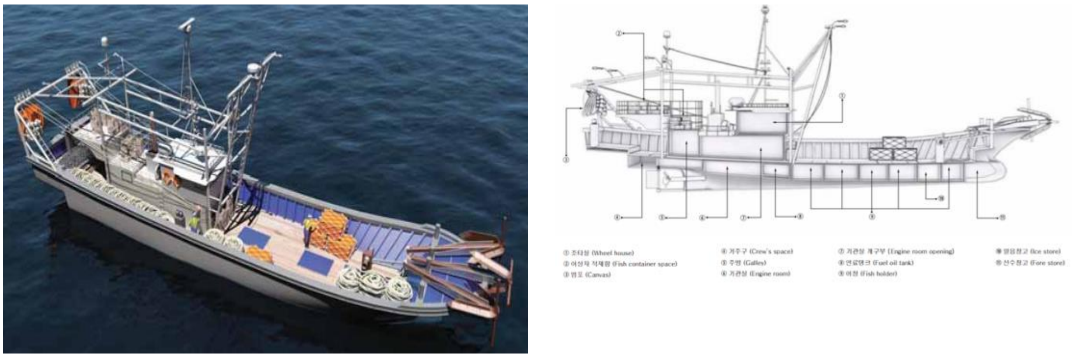


Figure 14: Example of 20 tonnage class Offshore Fishing Vessel (NIFS, 2017)

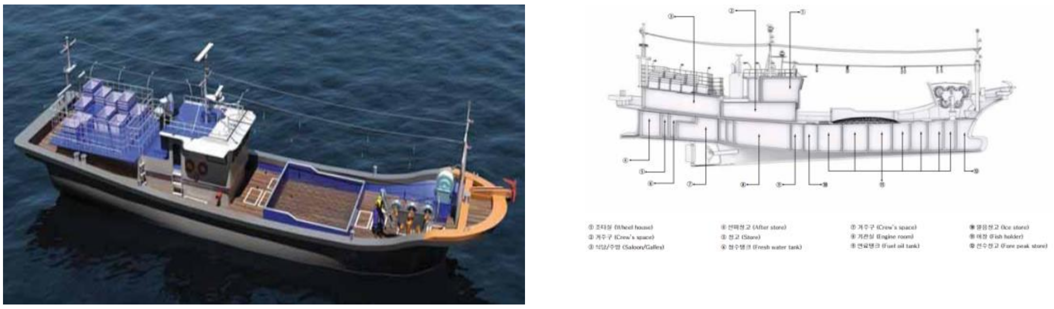


Figure 15: Example of 40 tonnage class Offshore Fishing Vessel (NIFS, 2017)

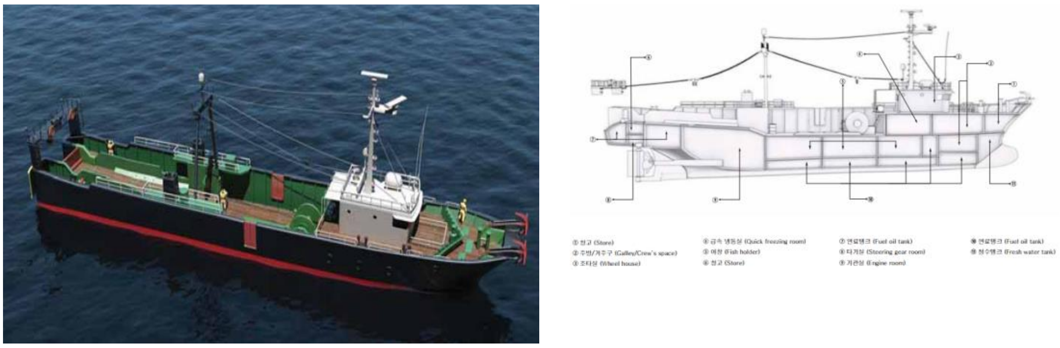


Figure 16: Example of 140 tonnage class Offshore Fishing Vessel (NIFS, 2017)

To estimate the required battery capacity and weight for a vessel built with specifications similar to those of currently operating offshore fishing vessels, vessel data relevant to the stability calculation were generated, as shown in Table 28, 29 and Table 30.

Table 28: Stability calculation data for 11 ~ 19 ton coastal fishing boats

Number	Tonnage	Lightweight	Displacement	Maximum Fuel Oil	Engine Power	
	(Ton)	(Ton)	(Ton)	(Ton)	(PS)	(kW)
1	11	28.927	57.764	4.925	497	365.3
2	12	28.761	46.568	2.758	648	476.3
3	13	21.065	52.602	3.255	608	446.9
4	14	43.595	70.457	4.917	497	365.3
5	15	41.563	67.867	7.476	450	330.8
6	16	32.026	67.231	4.03	480	352.8
7	17	28.268	50.423	5.325	388	285.2
8	18	31.126	58.089	8.786	748	549.8
Average	14.50	31.92	58.88	**5.18**	539.50	396.53

Table 29: Stability calculation data for 21 ~ 49 ton coastal fishing boats

Number	Tonnage	Lightweight	Displacement	Maximum Fuel Oil	Engine Power	
	(Ton)	(Ton)	(Ton)	(Ton)	(PS)	(kW)
1	47	100.012	170.143	46.268	1138	836.4
2	46	12.378	184.914	28.783	940	690.9
3	24	83.945	123.958	11.299	829	609.3
4	22	52.824	106.979	5.135	823	604.9
5	24	68.692	115.193	12.334	911	669.6
6	39	74.65	125.04	5.095	560	411.6
7	31	73.05	119.306	4.241	891	654.9
8	29	65.535	121.595	22.262	823	604.9
9	41	89.994	176.288	35.699	793	582.9
10	21	60.662	93.474	15.578	750	551.3
Average	32.4	68.1742	133.689	**18.669**	845.8	621.663

Table 30: Stability calculation data for 51 ~ 311 ton coastal fishing boats

Number	Tonnage	Lightweight	Displacement	Maximum Fuel Oil	Engine Power	
	(Ton)	(Ton)	(Ton)	(Ton)	(PS)	(kW)
1	51	89.318	158.831	11.832	1369	1006.2
2	88	221.55	336.851	27.737	1369	1006.2
3	76	161.749	293.311	19.278	1319	969.5
4	72	119.32	281.53	16.782	1369	1006.2
5	129	352.298	461.341	54.604	1160	852.6
6	131	238.695	460.65	80.003	1032	758.5
7	129	342.17	459.296	55.813	1170	860.0
8	129	352.345	446.37	49.028	1170	860.0
9	129	342.573	468.975	68.627	1170	860.0
Average	103.778	246.669	374.128	**42.634**	1236.444	908.787

In the table above, the average maximum fuel oil weight for vessels in the 11~19 ton category, it's approximately 18.7 tons, and for vessels in the 51~311 ton category, it's approximately 42.6 tons. This fuel weight, similar to coastal vessels, represents the weight of fuel when vessels depart, loaded to 98%. When considering propulsion and operation energy alone without considering other factors, it can be compared to the battery of an electrically driven vessel.

On the other hand, offshore fishing vessels typically have a daily navigation distance of about 100 NM, and the navigation time is given as 9 hours per day in Table o, so the navigation speed can be considered approximately 11.11 knots. Here, the engine load during navigation is 73%, so the maximum speed is approximately 15.22 knots.

The required energy for navigation (kWh), the required energy for operation (kWh), the expected battery volume (m^3), and the expected battery weight (ton) are the same as the calculation method for offshore fishing vessels.

Based on the above navigation information, the calculated energy requirements are shown in the following Table 31.

Table 31: Energy requirements for existing offshore fishing vessels

Category		**Average Propulsion Power**	**Maximum Speed**	**Engine load factor**		**Sailing**	**Daily working hours**		**Sailing Distance**	**Amount of required energy**	
Type	**Tonnage**			**Sail**	**Work**	**Speed**	**Sail**	**Work**		**Sail**	**Work**
	(ton)	**(kW)**	**(Knots)**	**(%)**		**(hours)**	**(hours)**		**(NM)**	**(kWh)**	
Offshore Fishing Vessels	10～20	400	15.22	73%	20%	11.11	9	39	100.00	2628	3120
	20～50	600	16.22	73%	20%	11.84	9	39	100.00	3942	4680
	50 ～	900	17.22	73%	20%	12.57	9	39	100.00	5913	7020

When aligning the weight of fuel oil from Table 28, Table 29, and Table 30 with the energy density of Li-ion batteries for vessels currently in operation, the results are as shown in Table 32.

For the 10~20 ton category, to satisfy the 5.2 m^3 volume requirement, a battery with a Volumetric energy density of 500 kW/m^3 must be applied, even though it exceeds the volume by 121% compared to the existing setup. To satisfy the 6.05 ton weight requirement, a Gravimetric energy density of 200 kW/ton must be applied, even though it exceeds the weight by a significant 375% compared to the existing setup.

For the 20~50 ton category, to satisfy the 18.7 m^3 volume requirement, a battery with a Volumetric energy density of 460 kW/m^3 must be applied, and to satisfy the 21.74 ton weight requirement, a Gravimetric energy density of 200 kW/ton must be applied, even though it exceeds the weight by 98% compared to the existing setup.

For the 50 ton and above category, to satisfy the 42.6 m^3 volume requirement, a battery with a Volumetric energy density of 304 kW/m^3 must be applied, and to satisfy the 49.54 ton weight requirement, a Gravimetric energy density of 200 kW/ton must be applied, even though it exceeds the weight by 31% compared to the existing setup.

Table 32: Required energy density of existing offshore fishing vessels

Category		**Maximum Fuel Oil**		**Energy density**		**Required Energy density**	
Type	**Tonnage**	**Volume**	**Weight**	**Volume**	**Weight**	**Volume**	**Weight**
	(ton)	**(m^3)**	**(ton)**	**(m^3)**	**(ton)**	**kWh/m^3**	**kW/ton**
Offshore Fishing Vessels	10～20	5.2	6.05	11.5	28.7	500	200
	20～50	18.7	21.74	18.7	43.1	460	200
	50 ～	42.6	49.53	42.5	64.7	304	200

Furthermore, using Crystal Ball in the same manner as with offshore fishing vessels, the maximum and minimum values of energy density are calculated, as shown in Table 33.

Table 33: Calculation of Energy density

Category			**Average Propulsion Power**	**Maximum Speed**	**Engine load factor**		**(1) Sailing**	**Daily working hours**		**Sailing Distance**	**Amount of required energy**		**Energy density**	
Type	**Tonnage**				**Sail**	**Work**	**Speed**	**Sail**	**Work**		**(2) Sail**	**(3) Work**	**(4) Volume**	**(5) Weight**
	(ton)		**(kW)**	**(Knots)**	**(%)**		**(knots)**	**(hours)**		**(NM)**	**(kWh)**		**(m^3)**	**(ton)**
Offshore Fishing Vessels	10 ~ 20	Min.	400	15.22	66%	18%	10.05	8.1	35.1	100.00	2138.4	2572.2	9.3	23.3
		Max.			80%	22%	12.18	9.9	42.9		3168	3775.2	34.7	92.6
	20 ~ 50	Min.	600	16.22	66%	18%	10.71	8.1	35.1	100.00	3207.6	3790.8	14.0	35.0
		Max.			80%	22%	12.98	9.9	42.9		4752	5662.8	52.1	138.9
	50 ~	Min.	900	17.22	66%	18%	11.37	8.1	35.1	100.00	4811.4	5686.2	21.0	52.5
		Max.			80%	22%	13.78	9.9	42.9		7128	8494.2	78.1	208.3

Similar to coastal fishing vessels, even if energy usage is generally 10% lower than average load, the required battery volume and weight increase.

When compared to the electric propulsion vessel's battery, which accounts for only propulsion and operation energy, the weight of the 11~19 ton class vessel is 23.3 tons (Volume 1.1 m^3), the 21-49 ton class vessel is 35 tons, and the 51-311 ton class vessel is 52.5 tons. This means that each is 348%, 87%, and 23% heavier, respectively, when considering the energy reductions from the current vessel's capabilities and the use of the highest-energy density existing batteries. Thus, like coastal fishing vessels, electric propulsion vessels for offshore fishing vessels need to increase battery weight even if they have approximately 10% lower performance than conventional vessels.

Therefore, considering battery capacity, a rough Concept General Arrangement for electrically powered vessels is proposed here, as illustrated in Figure 17, 18 and 19.

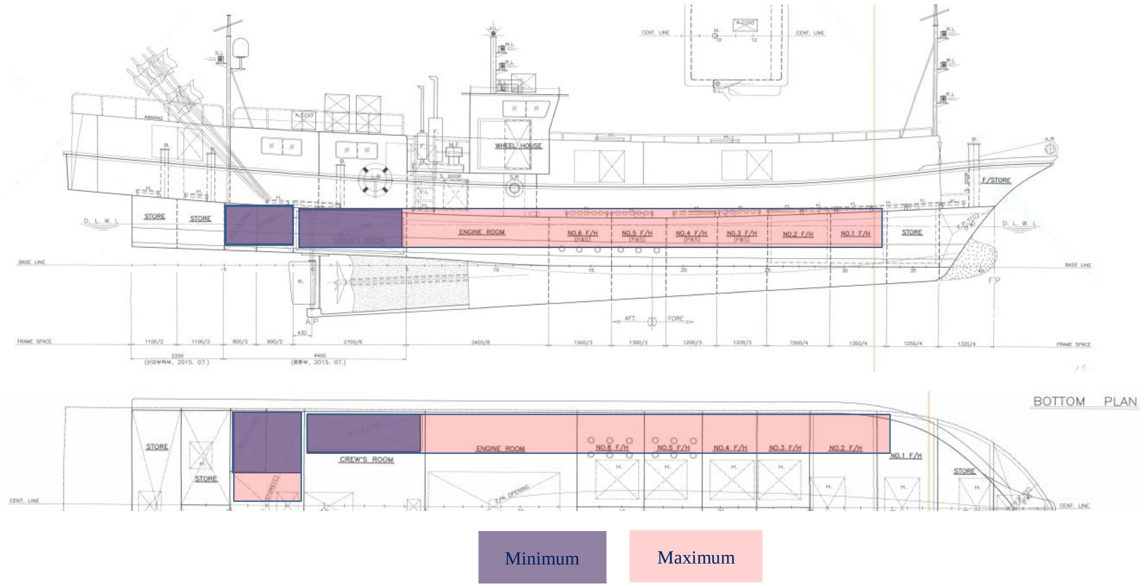


Figure 17: 15 ton class Concept Battery Arrangement for Offshore fishing vessels

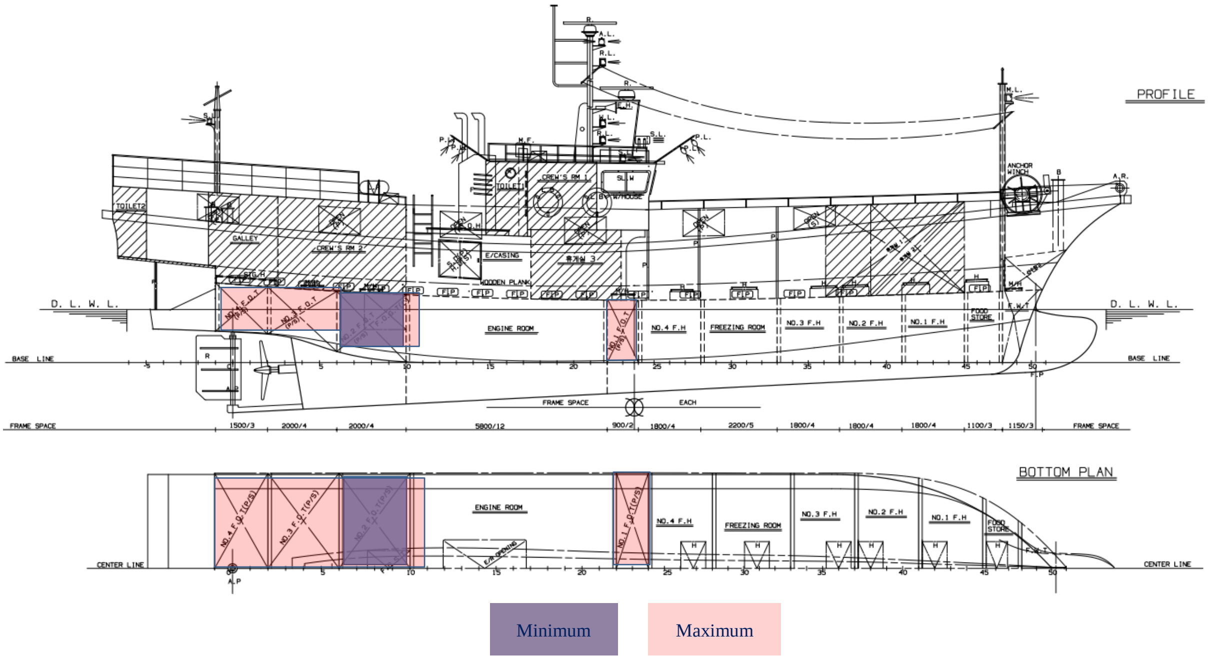


Figure 18: 30 ton class Concept Battery Arrangement for Offshore fishing vessels

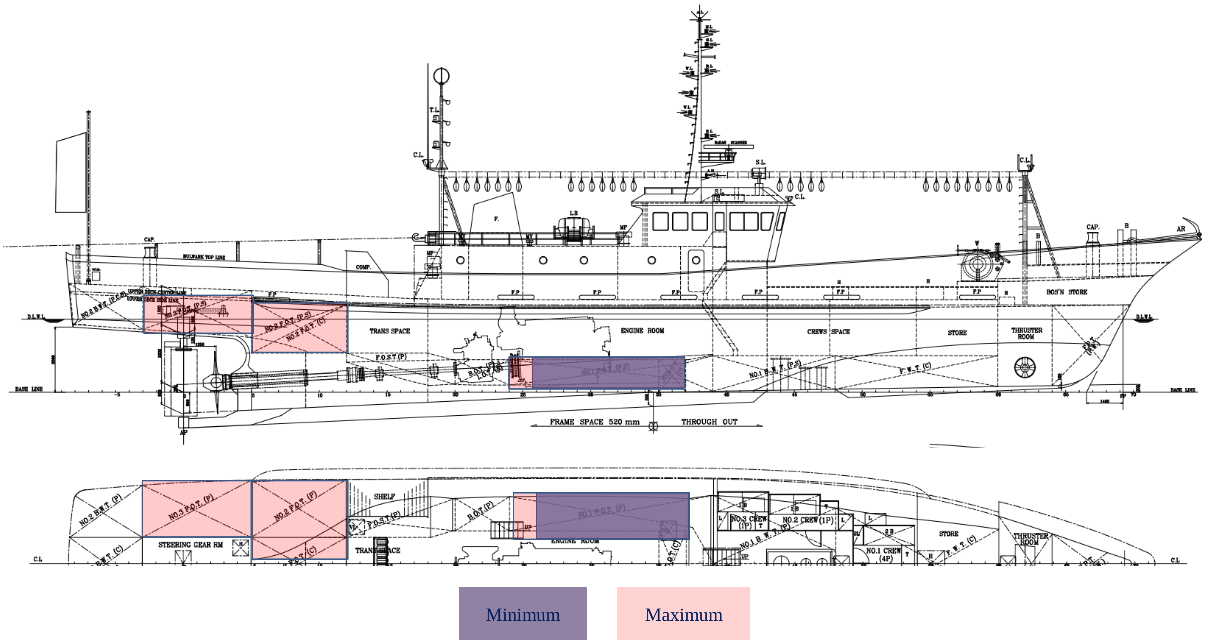


Figure 19: 107 ton class Concept Battery Arrangement for Offshore fishing vessels

The minimum and maximum battery capacities are as shown in the Table 34 below.

Table 34: Volume of Batteries for Stability calculation data for coastal fishing boats

Tonn-age	**Tank No.**	**Minimum**					**Maximum**				
		L	**B**	**D**	**Vol.**	**Sum**	**L**	**B**	**D**	**Vol.**	**Sum**
		(m)	**(m)**	**(m)**	**(m^3)**	**(m^3)**	**(m)**	**(m)**	**(m)**	**(m^3)**	**(m^3)**
15	No.1	2.70	1.21	0.80	2.61x2=5.2	9.3	15.11	1.21	0.80	14.63x2=29.3	34.7
	No.2	1.70	1.50	0.80	2.04x2=4.1		1.70	2.00	0.80	2.72x2=5.4	
30	No.1	2.00	2.50	1.40	7.00x2=14.0	14.0	2.00	2.50	1.40	7.00x2=14.0	52.1
	No.2	-	-	-	-	-	5.86	2.50	1.30	19.05x2=38.1	
107	No.1	5.84	1.50	1.20	10.51x2=21.0	21.0	6.76	1.50	1.20	12.17x2=24.3	78.1
	No.2	-	-	-	-	-	3.64	3.00	1.50	16.38x2=32.8	
	No.3	-	-	-	-	-	4.16	2.10	1.20	10.48x2=21.0	

5.2 EGTS for small fishing boats under 10 tons

In this Chapter, the patented small ship (EGTS), as discussed in Chapter 4.2, was applied to small vessels with a total tonnage of less than 10 tons. The optimal locations for the EGTS was examined and applied on the drawings of 3, 5, 7, and 9-ton-class vessels using the Autocad design program. An assessment was made to determine whether the applied EGTS has an impact on the vessel's stability.

5.2.1 EGTS installation on a 3 ton fishing boat

To install the EGTS on a 3 ton class vessel, it appears most ideal to install it on the external exhaust duct connected to the main engine, given the narrow engine room space. Typically, there is a silencer installed on the exhaust duct, as shown in Figure 20. Therefore, it seems feasible to remove the silencer and install the EGTS as depicted in Figure 21.

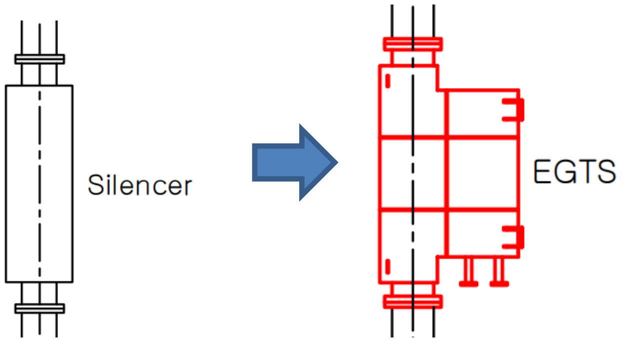


Figure 20: Installing EGTS after removing the silencer

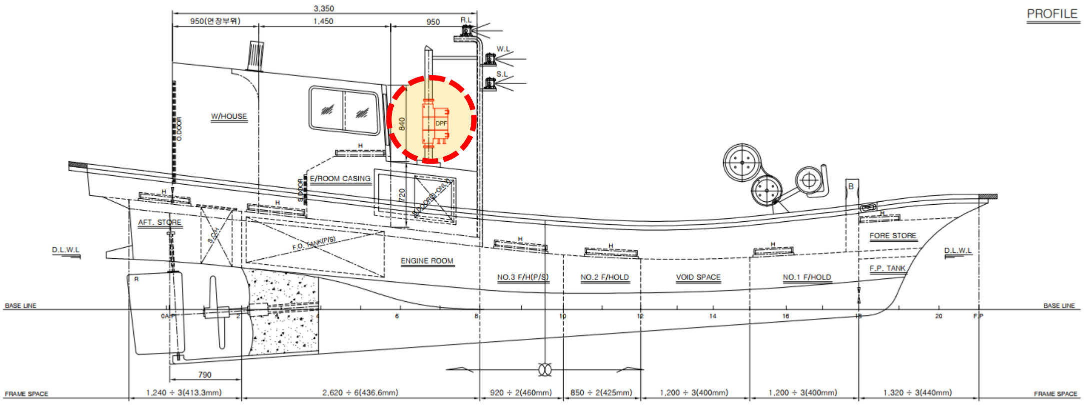


Figure 21: 3 ton small fishing boat with EGTS installed

5.2.2 EGTS installation on a 5 ton fishing boat

In the case of a 5 ton class vessel, similar to the 3 ton class vessel, it seems reasonable to expand the funnel, if present, to accommodate the EGTS internally, as shown in Figure 22, 23.

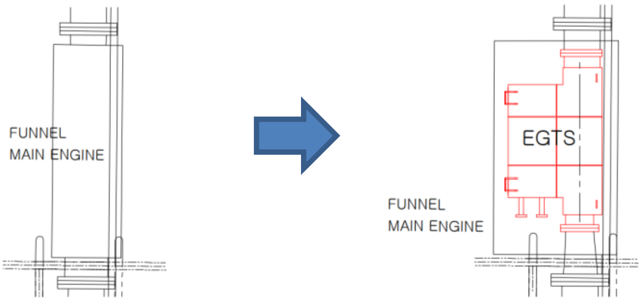


Figure 22: Expand the funnel to install EGTS inside

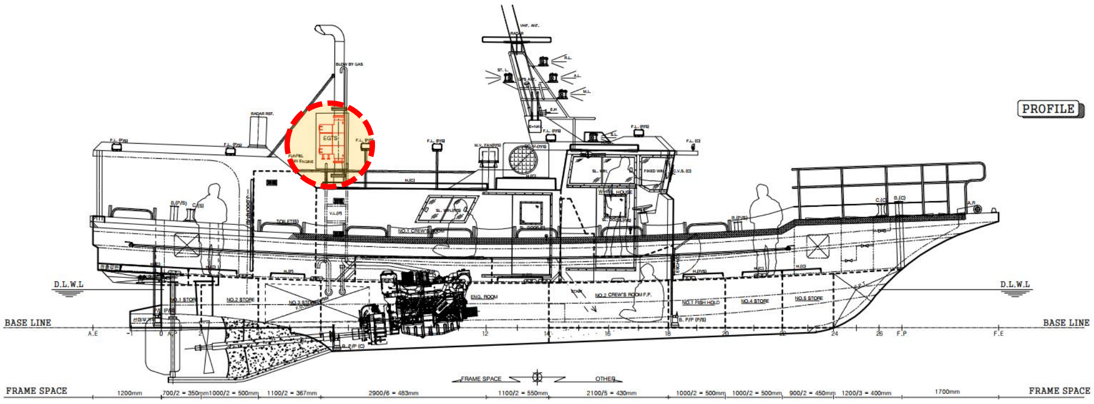


Figure 23: 5 ton small fishing boat with EGTS installed

5.2.3 EGTS installation on a 7.93 ton fishing boat

In the case of a 7 ton class vessel, similar to the 3 ton class vessel, it appears reasonable to remove the silencer and install the EGTS as shown in Figure 24.

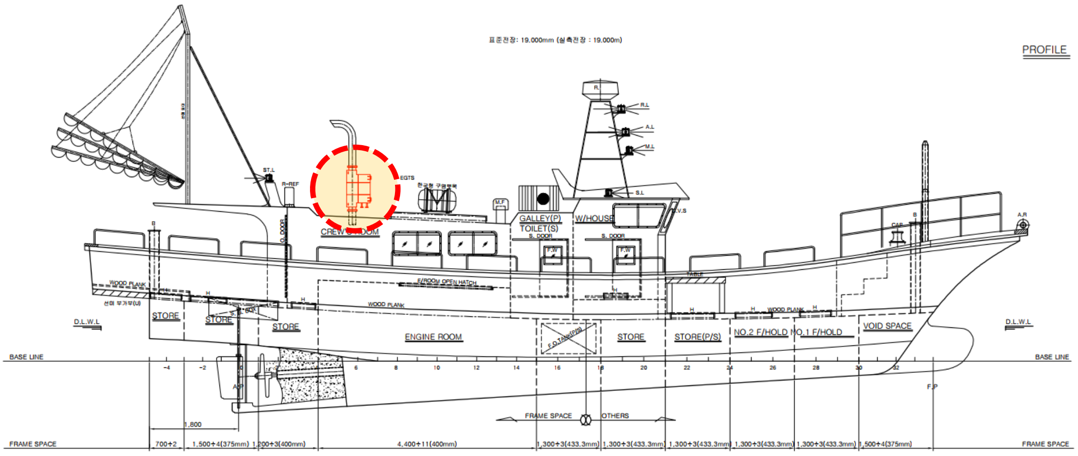


Figure 24: 7.93 ton small fishing boat with EGTS installed

5.2.4 EGTS installation on a 9.77 ton fishing boat

In the case of a 9 ton class vessel, there are situations where there is space available in the engine room to install the EGTS. Therefore, it has been illustrated as shown in Figure 25 and 26 to install the EGTS inside the engine room.

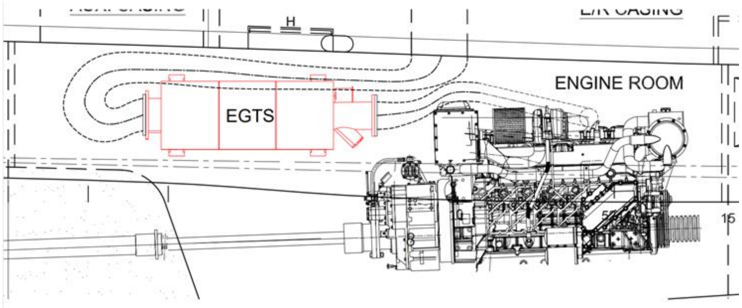


Figure 25: Install EGTS using free space in the Engine Room

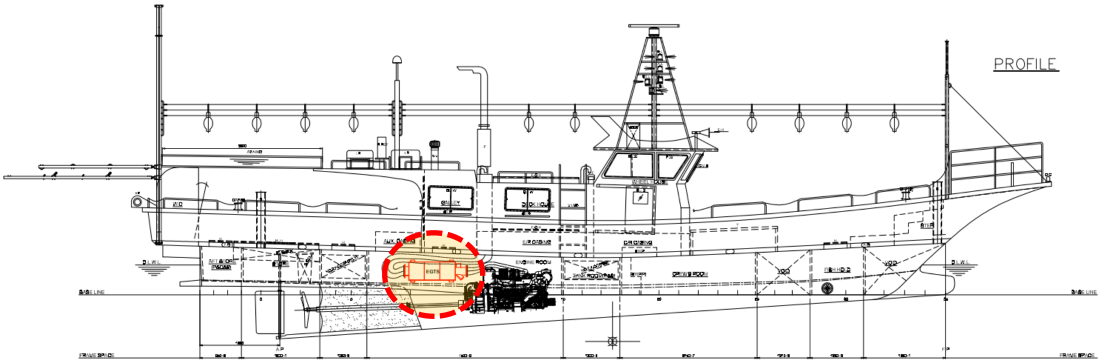


Figure 26: 9.77 ton small fishing boat with EGTS installed

5.3 Review of the impact of fishing vessel stability following EGTS installation

When installing EGTS on small vessels weighing less than 10 tons, it is planned to assess its impact on the vessel's stability. In the regulations of Republic of Korea regarding fishing vessels, there are circumstances where a Stability Test can be omitted, such as when installing EGTS. For small vessels weighing less than 10 tons, the following criteria are considered for determining that there are no stability issues, allowing the omission of the test or the rewriting of the Stability booklet. First, if the change in Lightweight is within 2% or less than the larger of 2 tons, or if the Longitudinal Center of Gravity (LCG) is less than 1% of the Length Between Perpendicular (LBP), the test can be omitted. Second, in cases where the installation or removal of equipment like EGTS leads to an increase in the Vertical Center of

Gravity (VCG), omitting the rewriting of the Stability Booklet is permissible if the difference in Lightweight is less than 0.5% for increasing VCG or less than 1.5% for decreasing VCG. In light of these considerations, a stability assessment is planned.

5.3.1 Determination of stability of 3 ton fishing boat

For a 3 ton class fishing vessel, it can be considered to install the EGTS in a location similar to where the silencer has been removed, as reviewed in Table 35 below.

The sequence of calculations is as follows:

First, record the Lightweight, LCG, and VCG from the Stability Calculation Booklet.

Second, verify the weight and position of items to be excluded and added. Sum all the weights, and calculate LCG and VCG as follows:

$$\bar{x} = \frac{\sum_{i=1}^{n} m_i x_i}{\sum_{i=1}^{n} m_i}, \bar{y} = \frac{\sum_{i=1}^{n} m_i y_i}{\sum_{i=1}^{n} m_i}$$

Third, to review the change in Lightweight, sum both the Deducted items and added items.

Fourth, to review the changes in LCG and VCG, calculate LCG and VCG considering the deducted items and added items obtained in the second step.

Table 35: Review of light weight of 3 ton fishing boat

Item	**Weight**	**LCG**	**LCG Moment**	**VCG**	**VCG Moment**
	(Ton)	**(m)**	**(Ton-m)**	**(m)**	**(Ton-m)**
Lightweight	8.085	-2.828	-22.864	0.824	6.662
Deducted Silencer	-0.2	-1.280	0.256	2.075	-0.415
Added EGTS	0.25	-1.211	-0.303	2.041	0.510
Review	**8.135**	**-2.816**	-22.911	**0.831**	6.757

After these calculations, compare the initial Lightweight, LCG, and VCG with the modified Lightweight, LCG, and VCG. The decision of whether to perform a Stability Test is determined based on the comparison, as shown in the following Table 36.

Table 36: Calculation results for reviewing whether to perform stability tests on 3 ton fishing boats

Item	**Before**	**After**	**+ / -**	*LBP (m): 9.600*	
	(Ton)	**(m)**	**(m)**	**Rate of change**	
Lightweight	8.085	8.135	0.05	0.6%	< 2%
LCG	-2.828	-2.816	0.012	0.1%	< 1%

The review results indicate that the increased Lightweight is smaller than 2 tons and falls within the range of 2%. Furthermore, the changed LCG is within the range of 1%. Therefore, the Stability Test can be omitted. However, in order to determine whether the Stability booklet needs to be rewritten, the variations in VCG were examined, as shown in the following Table 37.

Table 37: Calculation results for reviewing whether to rewrite the stability booklet of a 3 ton fishing boat

Item	**Before**	**After**	**+ / -**	**Rate of change**	
	(Ton)	**(m)**	**(m)**	**(%)**	
VCG	0.824	0.831	0.007	**0.8%**	> 0.5%

The review results indicate that the increase in VCG due to the installation of EGTS is greater than the permissible range of 0.5%. Therefore, the Stability booklet needs to be rewritten.

5.3.2 Determination of stability of 5 ton fishing boat

For 5 ton class vessels, the installation of EGTS inside the funnel is considered, and it can be reviewed as shown in the following Table 38.

Table 38: Review of light weight of 5 ton fishing boat

Item	**Weight**	**LCG**	**LCG Moment**	**VCG**	**VCG Moment**
	(Ton)	**(m)**	**(Ton-m)**	**(m)**	**(Ton-m)**
Lightweight	12.228	-1.770	-21.644	0.785	9.599
Added EGTS	0.3	-3.568	-1.070	3.304	0.991
Review	**12.528**	**-1.813**	-22.714	**0.845**	10.590

To determine whether a Stability Test needs to be conducted, calculations were performed as shown in the following Table 39.

Table 39: Calculation results for reviewing whether to perform stability tests on 5 ton fishing boats

Item	**Before**	**After**	**+ / -**	*LBP (m): 10.600*	
	(Ton)	**(m)**	**(m)**	**Rate of change**	
Lightweight	12.228	12.528	0.3	2.5%	> 2%
LCG	-1.770	-1.813	-0.043	0.4%	< 1%

The review results indicate that the Lightweight is larger than the allowable range of 2% but smaller than 2 tons, meeting the exemption criteria for the Stability Test. Additionally, the LCG remains within the range of 1%, so the Stability Test can be omitted. However, to determine whether it is necessary to rewrite the Stability booklet, fluctuations in the VCG were reviewed as shown in the following Table 40.

Table 40: Calculation results for reviewing whether to rewrite the stability booklet of a 5 ton fishing boat

Item	**Before**	**After**	**+ / -**	**Rate of change**	
	(Ton)	**(m)**	**(m)**	**(%)**	
VCG	0.785	0.845	0.060	**7.7%**	> 0.5%

The review results indicate that the increase in VCG due to the installation of EGTS exceeds the allowable range of 0.5%, necessitating the rewriting of the Stability booklet.

5.3.3 Determination of stability of 7.93 ton fishing boat

A 7.93 ton vessel, like a 3 ton vessel, is considered for the installation of EGTS after removing the silencer, as reviewed in the following Table 41.

Table 41: Review of light weight of 7.93 ton fishing boat

Item	Weight	LCG	LCG Moment	VCG	VCG Moment
	(Ton)	(m)	(Ton-m)	(m)	(Ton-m)
Lightweight	18.854	-1.360	-25.641	0.921	17.365
Deducted Silencer	-0.2	-4.716	0.943	3.435	-0.687
Added EGTS	0.35	-4.598	-1.609	3.478	1.217
Review	**19.004**	**-1.384**	-26.308	**0.942**	17.895

To determine whether a Stability Test needs to be conducted, calculations were performed as shown in the following Table 42.

Table 42: Calculation results for reviewing whether to perform stability tests on 7.93 ton fishing boats

Item	Before	After	+ / -	*LBP (m):*	*14.650*
	(Ton)	(m)	(m)	Rate of change	
Lightweight	18.854	19.004	0.15	0.8%	< 2%
LCG	-1.360	-1.384	-0.024	0.2%	< 1%

The review results indicate that both Lightweight and LCG are within the permissible ranges. To determine whether it is necessary to rewrite the Stability booklet, the variation in VCG was reviewed as shown in the following Table 43.

Table 43: Calculation results for reviewing whether to rewrite the stability booklet of a 7.93 ton fishing boat

Item	Before	After	+ / -	Rate of change	
	(Ton)	(m)	(m)	(%)	
VCG	0.921	0.942	0.021	**2.2%**	> 0.5%

The review results show that the increase in VCG due to the installation of EGTS exceeds the permissible range of 0.5%, so the Stability booklet needs to be rewritten.

5.3.4 Determination of stability of 9.77 ton fishing boat

For a 9.77 ton vessel, it is considered to install EGTS inside the engine room, and the assessment is presented in the following Table 44.

Table 44: Review of light weight of 9.77 ton fishing boat

Item	Weight	LCG	LCG Moment	VCG	VCG Moment
	(Ton)	(m)	(Ton-m)	(m)	(Ton-m)
Lightweight	22.642	-3.022	-68.424	1.234	27.940
Added EGTS	0.4	-4.134	-1.654	0.541	0.216
Review	**23.042**	**-3.041**	-70.078	**1.222**	28.157

To determine whether a Stability Test should be conducted, calculations were performed as shown in the following Table 45.

Table 45: Calculation results for reviewing whether to perform stability tests on 9.77 ton fishing boats

Item	Before	After	+ / -	*LBP (m): 15.620*	
	(Ton)	(m)	(m)	Rate of change	
Lightweight	22.642	23.042	0.4	1.8%	< 2%
LCG	-3.022	-3.041	-0.019	0.1%	< 1%

The review results indicate that both Lightweight and LCG fall within acceptable limits. To determine whether the Stability booklet should be rewritten, the following Table 46 was also examined.

Table 46: Calculation results for reviewing whether to rewrite the stability booklet of a 9.77 ton fishing boat

Item	Before	After	+ / -	Rate of change	
	(Ton)	(m)	(m)	(%)	
VCG	1.234	1.222	-0.012	1.0%	< 1.5%

The review results show that the installation of EGTS in the engine room has resulted in a decrease in VCG, and the rate of change is less than the acceptable range of 1.5%. Therefore, the Stability booklet can also be omitted.

Summary and Conclusions

This study investigated measures to reduce GHG and air pollutant emissions from fishing vessels operating in the waters of Republic of Korea.
Firstly, to calculate GHG and air pollutant emissions by vessel size and engine power, national statistics and data from KOMSA were utilized. Fuel consumption for vessels that operate in routes that are difficult to ascertain was estimated based on IPCC 2006 and EMEP/EEA 2013 guidelines, with differential assumptions made for engine power.

To reduce GHG emissions from fishing vessels, various alternative fuels were considered, but the TOPSIS methodology was applied to evaluate the feasibility of electric propulsion. To mitigate air pollutant emissions, the installation of EGTS was primarily examined for small vessels with a tonnage of less than 10 tons, focusing on those with relatively high pollutant emissions.

For electric propulsion vessels, performance comparisons were made among different tonnage classes in Republic of Korean waters. The study focused on calculating and arranging battery capacity for ship propulsion and operation, as it was deemed crucial in electric propulsion. Despite needing about 10% less energy than existing vessels, electric propulsion vessels would require significantly larger and heavier batteries. Even with the application of batteries with the highest density, a 23% to 348% increase in battery capacity was needed compared to conventional vessels.

Regarding EGTS, the study explored the installation of Republic of Korea's patented EGTS for small ships. Vessels were categorized into 2, 5, 7, and 9-ton classes to assess the placement of EGTS and its impact on stability. Removing the silencer and installing EGTS in its place was considered the simplest option, but it raised the vessel's center of gravity slightly due to increased weight. While stability tests may not be necessary after EGTS installation, updates to the Stability booklet would be required.

To achieve similar propulsion performance to current vessels, electric propulsion requires high-energy-density batteries. However, this poses technical challenges, and high-energy-density batteries come at a significant cost, making their installation less feasible. Therefore, a hybrid system that combines internal combustion engines with batteries may be a more viable option.

To install EGTS on small vessels with minimal impact on stability, the most effective approach is placing EGTS in the engine room. This maintains stability by avoiding an increase in the center of gravity. However, for smaller vessels with limited engine room space, developing EGTS specifically tailored for small ships could be a viable solution. If dedicated space for EGTS installation on small vessels can be secured, it would be the most desirable method for reducing pollutant emissions from small fishing vessels.

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