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Roadmap for the Decarbonization of Domestic Passenger Ferries in the Republic of Korea

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Abstract: This study examines the steps to lower air emissions in South Korea's domestic shipping sector. It highlights the significant contributions of the sector to air pollution and greenhouse gas emissions, emphasizing its impact on environmental sustainability and climate change mitigation. By looking at the current shipping energy use and emissions, the research identifies ways to reduce the environmental impact of domestic shipping. Data was collected from domestic ferry routes and the fuel use was reviewed with respect to existing global technologies for reducing emissions. The results show that operational changes and current energy-efficient technologies can quickly cut emissions. Furthermore, a long-term plan is suggested, involving the development of new ship designs and the use of net-zero fuels like biofuels, methanol, hydrogen and ammonia. These efforts aim to meet climate goals, targeting a 40% reduction in greenhouse emissions by 2030 and a 70% reduction by 2050, making South Korea's shipping industry more sustainable and resilient.

Keywords: emission reduction; energy efficiency; maritime industry; domestic shipping; alternative fuels; decarbonization

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1. Introduction

Maritime decarbonization has become a focal point in addressing global climate change. Despite accounting for only a small percentage of the total greenhouse gas emissions, the shipping industry contributes significantly to air pollution and climate-related effects due to its near-shore operations [1]. These emissions include carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), as well as notable levels of sulfur oxides (SO_X) and nitrogen oxides (NO_X), which are hazardous to both human health and the environment [2]. The International Maritime Organization (IMO) has made strides in regulating these emissions, adopting strategies and targets to significantly cut CO_2 and other greenhouse gases from shipping, highlighting the industry's commitment to achieving a sustainable and environmentally friendly future [3].

The Republic of Korea is taking crucial steps to address emissions from its domestic shipping sector, particularly focusing on passenger ferries. As a major player in the global maritime industry, Korea's shipping activities significantly impact its air quality and contribute to greenhouse gas emissions. Recognizing this, the government has implemented strategies to transform its domestic fleet, aiming for substantial emission reductions. This includes promoting the use of energy-efficient technologies and alternative fuels, with a dedicated roadmap to achieve sustainable operations within this vital sector of its economy [4].

The Republic of Korea has set ambitious targets to reduce greenhouse gas emissions in its domestic shipping sector as part of its broader climate strategy. By 2030, Korea aims for a 40% reduction in emissions compared to 2018 levels, escalating to a 70% reduction by 2050 (Figure 1). These targets are aligned with Korea's commitment to lowering its carbon footprint and supporting global efforts to mitigate climate change. Such initiatives include transitioning to eco-friendly maritime practices, investing in new technologies, and collaborating internationally, ensuring that Korea remains at the forefront of sustainable shipping and maritime advancements.

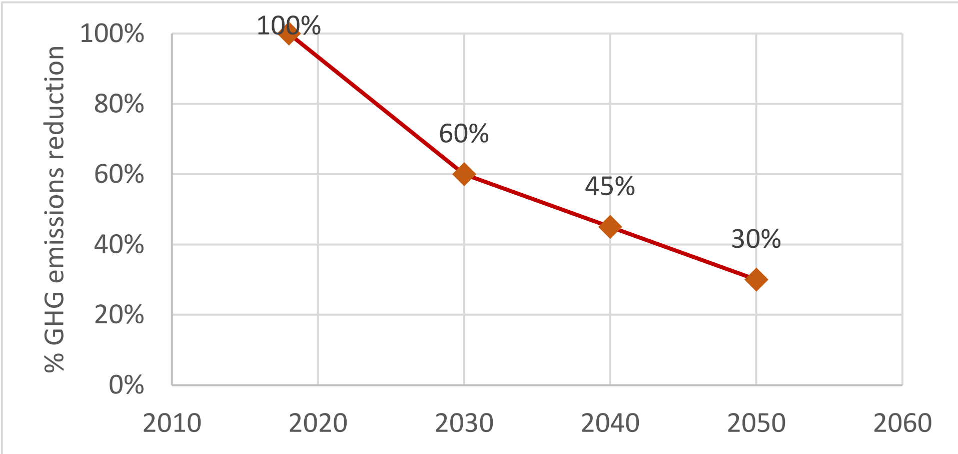

Figure 1. National targets for reductions in emissions for domestic shipping in the Republic of Korea [4].

This study explores the pathways for achieving decarbonization within Korea's domestic passenger ferry fleet. By examining the existing emission patterns and fuel consumption behaviors, this work seeks to develop and promote comprehensive strategies to transition towards zero-emission operations. This work outlines a clear roadmap for technological and operational improvements and sets the stage for pioneering efforts in maritime decarbonization. In particular, the novelty of this study lies in the fact that it studies and proposes ways to achieve this step by step by 2030, 2040, and 2050 from the perspective of the lifecycle based on the current policy direction and the shipping decarbonization goals of the Republic of Korea. This study aims to support Korea's national targets and enhance the resilience and sustainability of its maritime sector.

This manuscript is organized to explore how the Republic of Korea can reduce emissions in its domestic shipping industry. It starts by explaining the importance of shipping decarbonization and outlines Korea's current efforts. Next, it briefly reviews the different fuels, technologies, and policies available to cut shipping emissions. The third section describes the data used in the study, explaining how the data were collected and analyzed. The final section presents the results, focusing on mapping the domestic fleet's emissions, exploring ways to reduce these emissions, projecting the future fleet performance, and discussing a roadmap for achieving these goals.

2. Marine Fuels, Technologies, and Policy Initiatives for Decarbonization

2.1. Alternative Marine Fuels and Energies

Shipping decarbonization is accelerating and primarily depends on advancements in alternative fuels [5–7]. The variety of fuels is now at the forefront of the shipping industry's decarbonization efforts. In this sense, different studies have addressed alternative marine fuels, including hydrogen [8], ammonia [9], methanol [10], dimethyl ether (DME) [11], biofuels [12] such as hydrotreated vegetable oil (HVO) [13], and synthetic fuels [14]. Each fuel presents exclusive environmental values, specifically in cutting greenhouse gas (GHG) emissions, compared to conventional fossil fuels like heavy fuel oil (HFO). Hydrogen, for example, is considered a likely zero-emission fuel, chiefly when utilized with fuel cells, while ammonia is preferred owing to its well-established infrastructure in chemical shipping [15]. Methanol, which is easily handled and coheres with existing engines, has gained momentum as a low-emission alternative fuel [16].

Biofuels and synthetic fuels, particularly those derived from renewable sources, also contribute to reducing carbon emissions, although their extensive utilization is still limited by their availability and cost. Nonetheless, there are major barriers to the adoption of these fuels, remarkably related to their safety, infrastructure, and operational costs [17]. Hydrogen, while proffering high energy efficiency, needs large storage spaces due to its low volumetric density and presents serious safety concerns as it is highly flammable [10]. Ammonia, despite its smaller storage demand, creates considerable toxicity risks, making handling and safety measures critical issues [18]. Methanol, while easier to store and handle, has a lower energy density compared to that of traditional fuels, possibly resulting in higher fuel consumption [19]. These challenges are further compounded by the lack of established bunkering infrastructures for many of these fuels, predominantly hydrogen and ammonia, which limits their worldwide commercial implementation [20].

Across all alternative fuels, common challenges prevail, which include the high production costs, the lack of global supply chains, and the need for the broad retrofitting of vessels and infrastructure [15]. Safety concerns also continue to be the top priority, considering that most alternative fuels bring about risks either due to their flammability (e.g., hydrogen, DME) or toxicity (e.g., ammonia). The high capital and operational costs, in addition to the continuing need for regulatory development, make it tough for shipowners and operators to shift to these alternative alternatives in the short term [18]. In spite of these barriers, the constant progress in fuel technologies and policy provisions may help decrease the impact of such barriers and challenges, facilitating the decarbonization of maritime transport.

2.2. Technologies

A number of technologies are evolving as alternatives to traditional fossil fuel-based propulsion systems in the shipping industry. Internal combustion engines (ICEs) using alternative fuels are being developed to reduce carbon emissions and improve sustainability. These engines can run on a variety of fuels, such as hydrogen, ammonia, and methanol, offering greater flexibility and fuel efficiency [21]. Additionally, fuel cells, which convert chemical energy into electrical energy, present a favorable option with potential, especially for small ships and auxiliary power units [22]. Battery–electric engines, which depend wholly on electrical energy, are gaining traction for short-range and less power-demanding ships [23].

Carbon capture and storage (CCS) onboard ships is a technology designed to capture CO_2 emissions from exhaust gases, helping to reduce the ship's carbon footprint and move toward net-zero emissions without the need for alternative fuels, thereby helping in the transition period [10]. Other technologies, such as wind-assisted propulsion systems, hybrid power solutions combining multiple energy sources [24], and waste heat recovery systems [11], deliver additional opportunities for shipping decarbonization.

Recent advancements in hydrogen fuel cells and ammonia-fueled engines include improved safety measures and storage solutions, as demonstrated in pilot projects in Europe and East Asia [25,26]. Similarly, shipboard CCS trials have shown CO_2 capture efficiencies exceeding 85%, though challenges remain in terms of the retrofitting costs and infrastructure readiness [27].

These technologies deliver substantial environmental benefits. For instance, ICEs by means of alternative fuels can decrease the dependence on traditional fuels and lower carbon emissions, while fuel cells present greater energy efficiency, specifically when combined with renewable energy sources [15]. Battery–electric systems allow for zero-emission operations and lessen noise pollution, promoting a cleaner, quieter on- and offboard environment [28,29]. The utilization of renewable energy, such as photovoltaic power generation and wind-assisted propulsion systems, can also reduce fuel consumption (10–40%) and lower emissions, supporting shipping decarbonization targets [30].

While these technologies yield various benefits, they also encounter numerous barriers. Fuel cells need further technical advancements to develop their efficiency, dynamic response, and costs, while the infrastructure for hydrogen bunkering is still limited [31]. Battery–electric systems, though promising, are limited by their high initial costs and lower energy densities compared to traditional fuels, making them less favored for long-range ships [11]. Renewable energy systems such as photovoltaics and wind-assisted systems count profoundly on environmental conditions, which can constrain their effectiveness and reliability for seamless maritime operations [32]. Additionally, CCS faces barriers such as high installation and operational costs, technical challenges with retrofitting, and the need for CO_2 transport and storage infrastructure [33]. While renewable energy capture can improve energy efficiency and deliver complementary power for propulsion, it is still in the early stages of commercial adoption, which means that it needs further technological advancements, infrastructure investments, verification, and regulatory support to be wholly integrated into shipping operations.

2.3. Policy Initiatives for Domestic Ferries' Decarbonization

Most domestic fleets, particularly small vessels under 400 GT, are not subject to international energy regulations, such as the Ship Energy Efficiency Management Plan (SEEMP) for vessels above 400 GT, the Carbon Intensity Indicator (CII) calculation and Data Collection System (DCS) for vessels above 5000 GT, or the Energy Efficiency Design Index (EEDI) and Energy Efficiency Existing Ship Index (EEXI) for vessels above 400 GT [2,34,35]. The data from 160 ferries in South Korea indicate that only 40 vessels have capacities greater than 400 GT (the threshold for SEEMP applications), and only 10 exceed 5000 GT (the threshold for IMO DCS and CII applications). Because of this, alternative national policy initiatives tailored specifically for this sector are clearly necessary to compensate for the lack of coverage by binding energy regulations. The policy encompasses a wide range of vision–mission–action elements, such as strategy and goal setting, action plans and guidelines, binding rules and regulations, voluntary schemes, capacity building, and monitoring, reporting, and dissemination [36].

2.3.1. Decarbonization Strategy

A key component of the policy is the establishment of a decarbonization strategy, which may begin with the creation of the energy baseline and setting the decarbonization goals, followed by the development of a roadmap and several approaches and action plans to achieve these objectives. Setting decarbonization goals should take into account both national and international pledges. On an international level, the IMO GHG strategy may be a suitable option for allocating milestones in Korea's grand strategy for decarbonizing its ferry fleet. The Korea Nationally Determined Contributions (NDCs), the share of the Korea maritime industry in the NDCs, and the potential for the decarbonization of the ferry fleet must be considered at the national level. In order to encourage the industry to move forward, it is essential to set ambitious yet realistic goals for ferry fleet decarbonization.

2.3.2. Non-Mandatory Guidelines

Guidelines can serve several purposes, including demonstrations of how to conduct inspections and audits, and how to measure, calculate, and report. There are a variety of stakeholders who may benefit from guidelines, including policy implementers (e.g., flag states and port state control), policy implementers (e.g., shipping companies), as well as other stakeholders (e.g., charterers, maritime education and training institutes (METIs), and ports). In the absence of binding national and international regulations, Korean maritime authorities can develop guidelines, for instance, to introduce efficient shipping routes and domestic green corridors in South Korea to support METIs in the design of a training curriculum for alternative fuel handling courses for seafarers, to establish energy management systems in ports and shipping companies, to encourage ESG reporting in ports and shipping companies, and to prepare GHG emission inventories in ports. Furthermore, since there are no international codes or standards regulating the marine applications of alternative fuels, guidelines developed by the Korea Maritime Institute (KMI) in collaboration with subject experts from the Korean Register of Shipping (KR), Korean shipyards, and universities for the bunkering, storage, and usage of marine alternative fuels could be of considerable value in the current transition period.

2.3.3. Voluntary Programs with a Focus on Energy Efficiency

Incentive programs

Creating national incentive programs. A national incentive scheme could be introduced by the Korean government by taking inspiration from other local incentive programs around the world. There are several local port initiatives, such as the Cruise Ship Environmental Award, provided by the Cruise Terminal Environmental Advisory Committee (CTEAC) of the Port of San Francisco; the EcoAction Program and Blue Circle Award provided by the Port of Vancouver, Canada; and the Maritime Singapore Green Initiative, which includes (1) a Green Ship Program and (2) a Green Port Program [35]. In Korea, there is already a Green Ship Certificate and a Green Ship Program in place. A Green Ship Certificate is awarded to qualified initiatives, and the Green Ship Program provides financial assistance for the design and construction of green ships. The Green Ship Certificate has been in place since 1998. Upon adapting the necessary equipment or technology to reduce GHG emissions and air pollutants, a certificate is issued to the ship. A portion of the construction costs of new green ships built since 2011 have been subsidized by the Green Ship Program. Obtaining financing for new ships requires a certificate [37]. This approach underscores the importance of balancing economic feasibility with environmental objectives in decarbonization strategies. Therefore, the KMI should investigate possible methods of encouraging Korean ferry companies to apply for this national incentive program. To this end, it would be very beneficial to conduct a comprehensive study to investigate the barriers preventing ferry companies from joining this program.

Balancing environmental protection with the economic interests of the shipping industry is crucial for an effective decarbonization strategy. In Korea, incentive programs such as the "2030 Greenship-K Promotion Strategy" already play a pivotal role in reducing emissions while alleviating the financial burden on shipowners [38]. This program provides financial support for the adoption of green technologies and the construction of eco-friendly vessels. By demonstrating that sustainability and economic viability can align, this program helps shipowners achieve long-term cost savings while advancing environmental goals.

Joining international incentive programs. Major international incentive programs include the Environmental Shipping Index (ESI), the Clean Shipping Index (CSI), and the Green Award. It is important that Korean ports and ferry fleets participate in global incentive schemes in order to contribute to the decarbonization of this industry.

Voluntary agreements in ports.

Since voluntary emission reduction initiatives are more likely to succeed than those accompanied by legal requirements or compensation, port authorities promote voluntary initiatives to reduce emissions [39]. In order to reduce air emissions and become more energy-efficient, port tenants and port landlords can enter into voluntary agreements with port authorities. As a result of the signing of such agreements, ports, ships, and land transport operators enhance their environmental reputations and win awards and recognitions in addition to gaining a number of advantages, such as preferential berthing and reduced inspections [40]. Comparative analyses of successful initiatives, such as the Maritime Singapore Green Initiative and the Port of Vancouver's EcoAction Program [41,42], provide actionable insights for Korean ports. These programs incentivize emission reductions through measures like preferential berthing and reduced fees, which can serve as a model for designing voluntary agreements tailored to the specific needs of Korea's shipping sector.

2.3.4. National (and Regional) Economic Instruments

Several regions and countries have already developed their own carbon pricing systems as a result of the slow pace of negotiations regarding the introduction of a global carbon pricing mechanism for the shipping industry. Carbon pricing mechanisms such as the European Emission Trading System (EU ETS), the Shanghai ETS, and the Norwegian carbon tax are examples of regional and national mechanisms that include domestic and international shipping. From 2025, all offshore and general cargo ships exceeding 400 GT will be covered under the EU MRV and probably in the future under the EU ETS (currently, ships exceeding 5000 GT are included under the EU ETS) [43]. As a result of the expansion of the regulatory scope of the EU ETS, the Republic of Korea may be able to learn how to incorporate ferries with a capacity of 400 GT and above into its national carbon pricing system. It will be beneficial for the KMI to learn how to monitor and apply carbon taxes to small ferries, and how to recycle carbon revenue to support decarbonization activities within this niche market.

As part of the Chinese regional pilot program for emission trading schemes that includes both ports and domestic shipping, the Shanghai ETS was introduced in 2013 [44]. Similarly, Norway's domestic shipping industry is subject to a carbon tax. Depending on the fuel source, the carbon tax rates for inland transport vary. The highest rate applies to petrol, while the lowest rate applies to heavy mineral oils. Norway currently applies the standard carbon tax rate to LNG and LPG consumption in domestic shipping [44]. Despite the fact that NOx does not fall under the GHG category, the structure and performance of the Norwegian NOx Fund in tax collection and revenue recycling [45] may serve as an inspiration for Korean maritime authorities. A balanced approach combining robust policy support and well-designed market mechanisms, such as carbon pricing and financial incentives, is crucial for ensuring the decarbonization of the shipping industry while maintaining economic sustainability. A comprehensive carbon pricing mechanism for Korea could integrate lessons from the EU ETS and Norway's carbon tax systems, ensuring adaptability to the local vessel size distribution and operational characteristics. Recycling carbon revenues into green technology adoption and infrastructure development would strike a balance between policy support and market-based incentives, driving sustainable decarbonization.

2.3.5. Training and Capacity Building

The shipping industry can mitigate its carbon footprint through capacity-building programs such as technical assistance, training, and public awareness campaigns. The provision of training and reskilling for seafarers and ship operators is essential for ensuring a smooth and equitable energy transition [46]. According to [47], in the medium- and long-term future, seafarers should acquire skills relevant to handling advanced technologies adapted to ships to improve their operational safety and energy efficiency. METIs in Korea can take proactive steps to include these skills in their curricula.

2.3.6. Knowledge and Data Dissemination

Energy efficiency in the shipping industry is hindered by the availability of imperfect information. It could be characterized by a lack of information, a lack of reliable information, inaccurate information, a lack of information disclosure and transparency, as well as an improper form of information [48]. It is possible to enhance innovation and decarbonization efforts by collaborating with consultancy, energy management, technology, and manufacturing companies, as well as research and development firms and universities [40,49]. By publishing technical bulletins by maritime associations in Korea, ferry shipping companies will be able to evaluate their performances and adapt their CO_2 mitigation plans. The following information may be included in these technical bulletins: the latest status of the infrastructure readiness in Korean ports (including cold ironing equipment, battery-charging equipment, and bunkering facilities for alternative fuels), the latest technology adoption statistics, a review of shipyard order books, and best practices in domestic ferry fleets around the globe.

2.3.7. Monitoring and Reporting

The monitoring and reporting of the energy performances and emission inventories of ports and shipping operations are essential. In this direction, ports and shipping companies can disseminate information regarding their energy efficiencies and decarbonization initiatives. Environmental, Social, and Governance (ESG) reporting is a popular way of promoting environmental sustainability in ports and shipping companies. Since strategic decisions have a long-term impact, ESG is directly related to strategic planning, which involves the inclusion and implementation of new technologies, the use of natural resources, as well as the interaction between employees and the community [50]. As a matter of fact, most companies that possess strong sustainability standards and better ESG performances have lower capital costs, higher cash flows, improved operational performances, and better financial metrics [51]. Various ports that are pioneers in data reporting and dissemination have published ESG reports not only to outline the scope of such reports, but also to highlight the best practices and areas for improvement. It is recommended that the KMI develop an ESG reporting template for Korean ports based on a review of the existing ESG reports from different ports around the world and brainstorming workshops with Korean ports.

2.3.8. Domestic Green Shipping Corridors

A global campaign is underway to achieve carbon neutrality in the shipping industry by 2050 through the construction of international and domestic green shipping corridors (GSCs). The goal of GSCs is to establish a corridor cooperation system after analyzing the key aspects of the routes through pre-feasibility studies. During the establishment of domestic GSCs in Korea, there is a need to make urgent modifications and improvements to the ability to produce eco-friendly fuels, the supply chain, port facilities, and vessels that can transport alternative fuels. It is also necessary to have legal support for the establishment of a national action plan (NAP) including decarbonization strategies and stakeholder analyses. In addition, active policy cooperation between the related Korean ministries—the Ministry of Oceans and Fisheries and the Ministry of Industry—is crucial.

2.3.9. Emission and Fuel Consumption Standards

The IMO's regulations, such as the EEDI and EEXI, set benchmarks for energy efficiency in new and existing vessels, while the CII promotes ongoing operational improvements. South Korea's National Action Plan targets a 40% GHG reduction by 2030 and a 70% reduction by 2050 compared to the 2018 levels as presented in Section 1. These standards are guiding efforts to improve the energy efficiency and adopt low-carbon technologies in the domestic fleet.

3. Methodology and Data

This section outlines the steps taken to study how to reduce emissions in Korea's domestic shipping fleet. It includes data collection about the fleet, a review of the existing research on decarbonization, an analysis of the future fleet performance under different fuel scenarios, expert consultations on the feasibility of various technologies, and the development of a roadmap to guide the transition to zero emissions (Figure 2). In Section 2, the potential measures, such as fuels and energy sources, technologies, and policy initiatives, serve as valuable components for developing the roadmap outlined in Section 4.

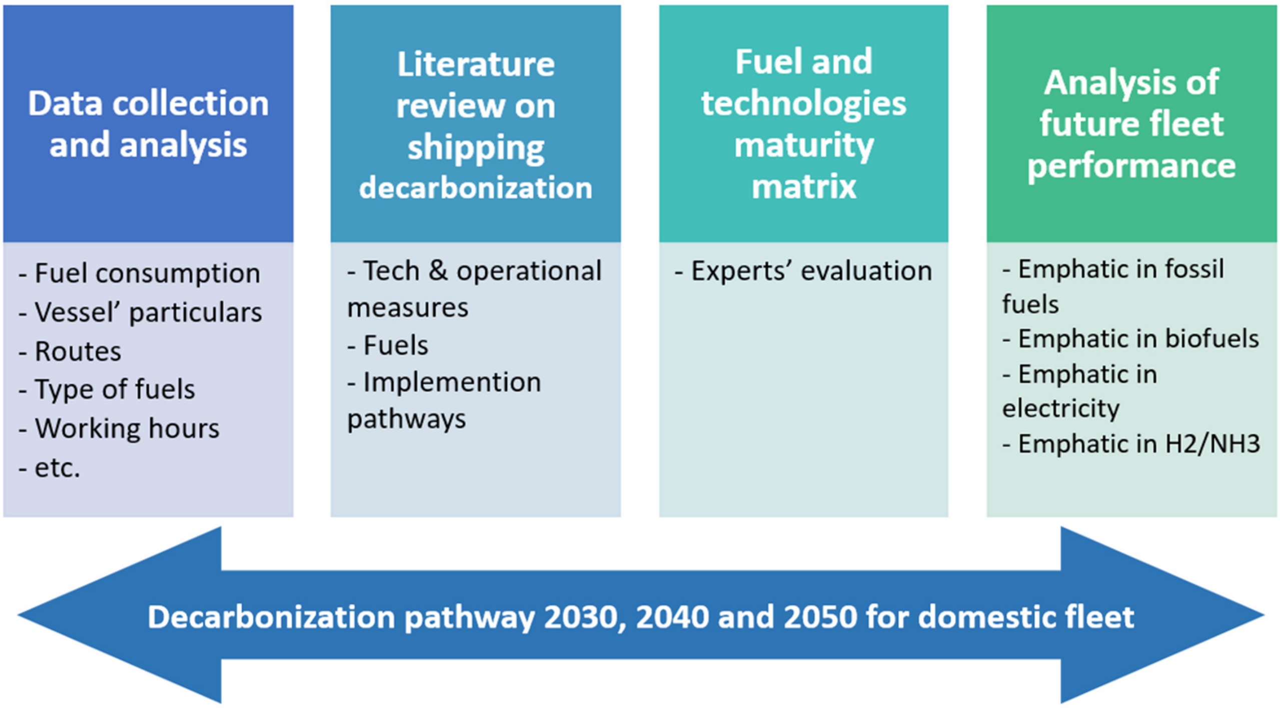

Figure 2. Framework of the research.

3.1. Data Collection and Analysis

The foundation of this study was built on the comprehensive collection of data concerning the Republic of Korea's domestic fleet. These data encompass essential attributes, such as the vessel size, age, operational routes, fuel consumption, and emission levels. This study aims to map out the fleet's characteristics, enabling an in-depth understanding of its current environmental impact. Data analysis involved segmenting the fleet based on various factors, which, in turn, facilitated the calculation of the total fuel consumption and greenhouse gas emissions.

Data collection from the Korean domestic fleet: The foundation of this project hinged on the extensive gathering of reliable data pertinent to the characteristics and operations of the Republic of Korea's passenger ferry domestic fleet. This phase was crucial for establishing an accurate dataset. After data acquisition, an analysis was conducted to map the fleet's characteristics. The assessment focused on fuel consumption and emissions, involving calculations of the total fuel use and greenhouse gas (GHG) emissions. The fleet was segmented by the vessel size, age, and operational patterns to determine its environmental impact.

3.2. Future Fleet Performance Analysis

To explore the future performance of Korea's domestic shipping fleet, this study used a scenario-based approach. This method involved creating four different scenarios to evaluate the effects of various fuel types and technologies: the increased use of fossil fuels, the greater deployment of biofuels, more reliance on battery and electric technologies, and the expanded use of hydrogen and ammonia. Each scenario was carefully designed to reflect the possible energy arrangements, considering Korea's goal of reducing greenhouse gas emissions by 40% by 2030 and by 70% by 2050. This analysis was valuable for identifying which paths could effectively help achieve these objectives, as well as for understanding the potential impacts of these changes on emissions and fleet operations.

The scenarios also examined how the fleet would operate, keeping energy demands steady while changing fuel types. By analyzing fleet operations with either a 50% or 80% use of alternative or traditional fuels, this study offers a detailed perspective on future energy consumption patterns. This thorough evaluation aimed to predict realistic outcomes and highlight the necessary technological changes to help the fleet reach national emission targets. The fuel mix and emission factors, well-to-tank (WTT), tank-to-wake (TTW), and well-to-wake (WTW), are in Tables 1 and 2. The data on emission factors are taken from [52]. It is assumed that the WTT emission factor of MGO is equal to that of HFO.

Table 1. Fuel mix in a 50% scenario: WTT, TTW, and WTW emission factors (kg CO_2 eq./GJ) for different fuels and their energy shares under various emphases.

Fuels	WTT (kg CO_2 eq./GJ)	TTW (kg CO_2 eq./GJ)	WTW (kg CO_2 eq./GJ)	Emphatic in Fossil Fuels	Emphatic in Biofuels	Emphatic in Battery/Electricity	Emphatic Hydrogen/Ammonia
MGO	15.90	76.78	92.68	20%	10%	0%	0%
LNG	17.60	76.03	93.63	30%	10%	0%	10%
Electricity	50.00	0.00	50.00	10%	10%	50%	10%
e-ammonia	2.86	0.00	2.86	10%	10%	10%	30%
Biomethane	−37.78	72.99	35.21	10%	20%	10%	10%
Biomethanol	−58.01	69.10	11.09	10%	10%	10%	10%
Biodiesel	−54.01	76.24	22.23	10%	20%	10%	10%
e-hydrogen	2.43	0.00	2.43	0%	10%	10%	20%

Table 2. Fuel mix: 80% scenarios: WTT, TTW, and WTW emission factors (kg CO_2 eq./GJ) for different fuels and their energy shares under various emphases.

Fuel	WTT (kg CO_2 eq./GJ)	TTW (kg CO_2 eq./GJ)	WTW (kg CO_2 eq./GJ)	Emphasis on Fossil Fuels	Emphasis on Biofuels	Emphasis on Battery/Electricity	Emphasis on Hydrogen/Ammonia
MGO	15.90	76.78	92.68	40%	0%	0%	0%
LNG	17.60	76.03	93.63	40%	0%	0%	0%
Electricity	50.00	0.00	50.00	5%	5%	80%	5%
e-ammonia	2.86	0.00	2.86	0%	5%	5%	40%
Biomethane	−37.78	72.99	35.21	5%	40%	5%	5%
Biomethanol	−58.01	69.10	11.09	0%	5%	5%	5%
Biodiesel	−54.01	76.24	22.23	5%	40%	0%	5%
e-hydrogen	2.43	0.00	2.43	5%	5%	5%	40%

This work also investigated the cost analysis and GHG abatement costs for the above scenarios. The fuel cost estimates are based on data from [52], as presented in Figure 3.

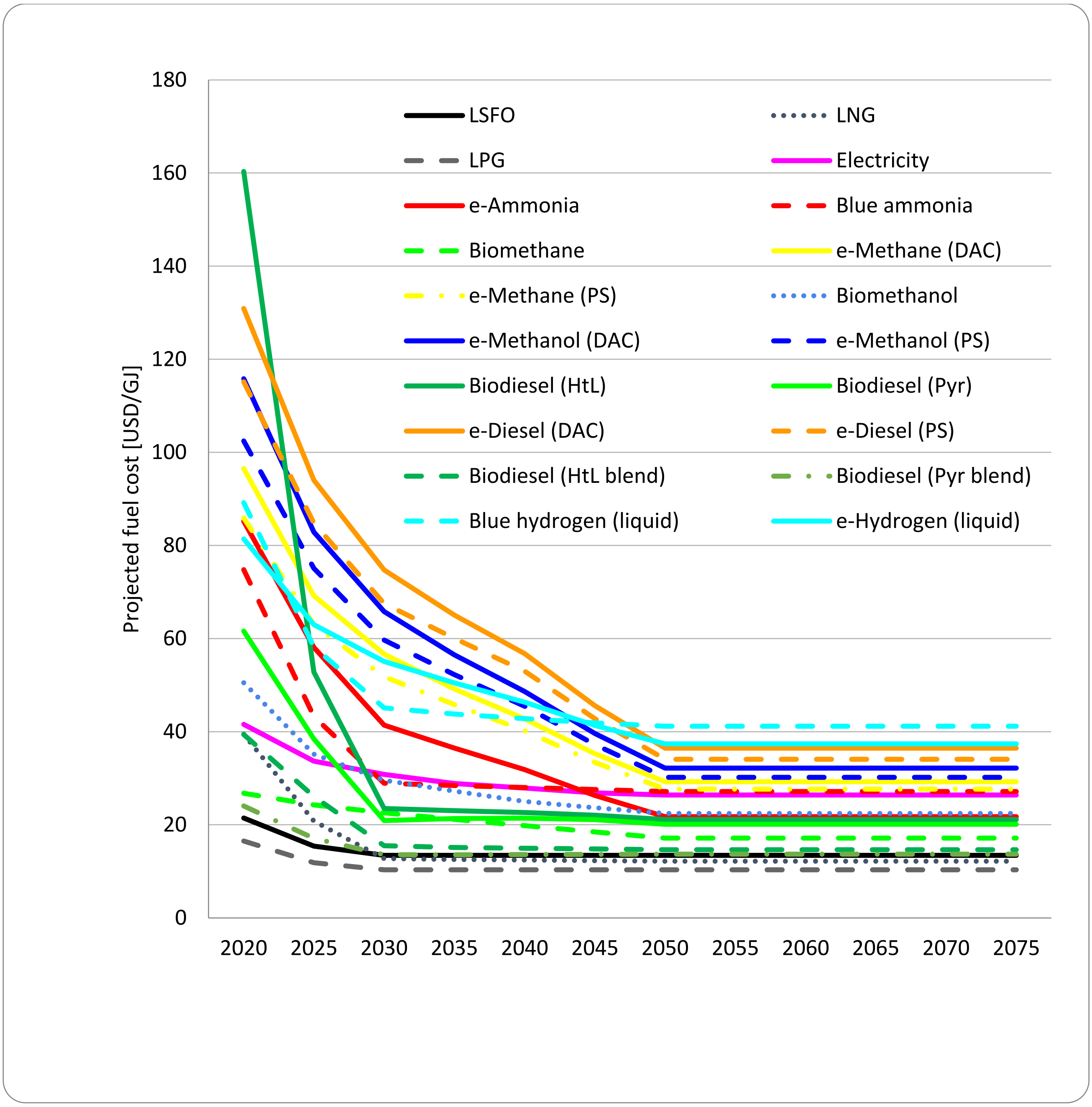

Figure 3. Fuel cost projection [52].

3.3. Research on Fuel and Technology Maturity

The assessment of the fuel and technology maturity involved working with experts to see how ready and useful different methods are for reducing emissions in the fleet. First, these methods were divided into three main groups: operational improvements, new technologies and ship designs, and alternative fuels. Experts looked at measures like slow steaming, hull coatings, just-in-time arrival (JIT), and hybrid systems, sharing their insights on how these could help lower emissions in different types of vessels and operating conditions.

In the next step, experts from various backgrounds, including ship designers and marine engineers, assessed how practical these methods are for different types of ships, such as small, medium, and large vessels. The ships were also sorted by age, route, and speed to ensure the analysis was relevant to their specific features.

3.4. Establishing a Roadmap for Net-Zero Domestic Passenger Fleet

Using the data collected, analyses conducted, and expert evaluations, a detailed roadmap was developed to help Korea's domestic fleet move towards achieving zero emissions. The roadmap aligns with both national and international climate goals, focusing on reducing emissions, improving energy efficiency, and encouraging sustainable practices. The roadmap also establishes clear milestones to track progress and ensure that plans are carried out on time. The strategic plan will help stakeholders work together effectively and create a collaborative environment aimed at reaching the ambitious decarbonization targets set for the short, medium, and long term.

4. Results and Discussion

4.1. Analysis of Domestic Fleet

4.1.1. Emissions from Domestic Passenger Ferries

Figure 4 presents the contribution of TTW emissions for marine gas oil (MGO) from the domestic passenger ferry fleet. Since most vessels in the domestic fleet use MGO as their marine fuel, CO_2 accounts for about 94% of the total TTW emissions, which includes local pollutants. Additionally, significant amounts of NO_X are produced from MGO use in marine engines. Figure 4 also provides insights into the contributions of greenhouse gas (GHG) emissions to GWP100 from the current domestic fleet. The results indicate that CO_2 is the dominant contributor to climate impact, far exceeding the impacts of other emissions. However, it is also important to note that N_2O contributes significantly to GWP100, highlighting that while CO_2 has the largest share, other gases like N_2O also play a considerable role in the overall climate effects of the fleet.

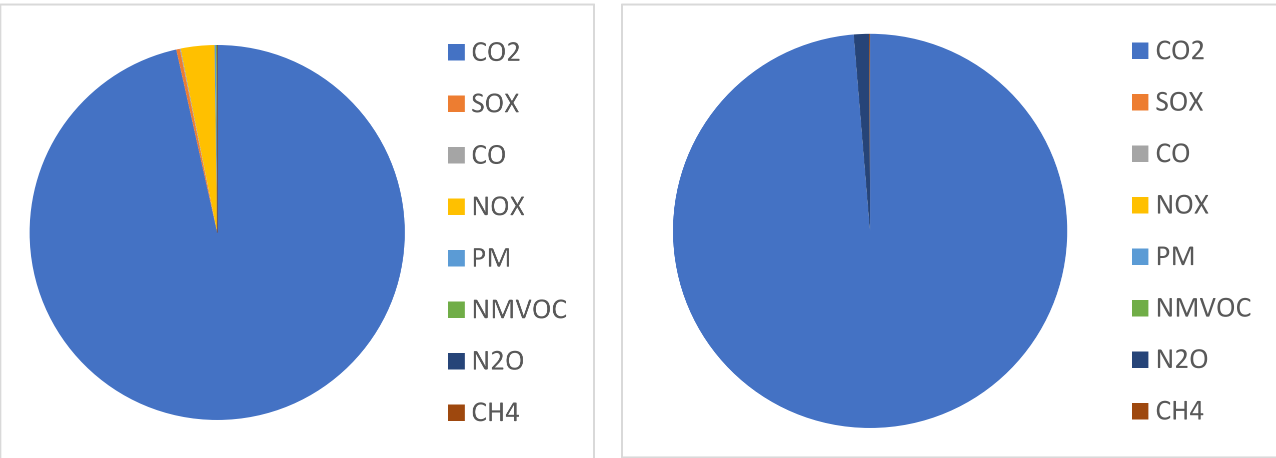

Figure 4. Contributions of TTW emissions from domestic ferry fleet (**left**) and contributions of emissions to GWP100 (**right**).

4.1.2. Fleet Specification

The vessels are grouped into four categories: new, young, middle-aged, and old. The new category includes 25 vessels that are less than five years old, with a total energy consumption of 10,047 tons of MGO, which makes up 21% of the total energy used. The young category has 58 vessels between 5 and 9.99 years old, consuming a total of 16,721 tons of MGO, representing 35% of the overall energy usage in the dataset. The middle-aged group includes 21 vessels that are between 10 and 14.99 years old, with a combined energy consumption of 8442 tons of MGO, accounting for 18% of the total energy use. Finally, the old category consists of 56 vessels aged between 15 and 30 years, which consume 12,512 tons of MGO, making up 26% of the total energy consumption (Figure 5). Figure 6 shows the energy consumed by each age group, with the assumption that the energy demand remains unchanged.

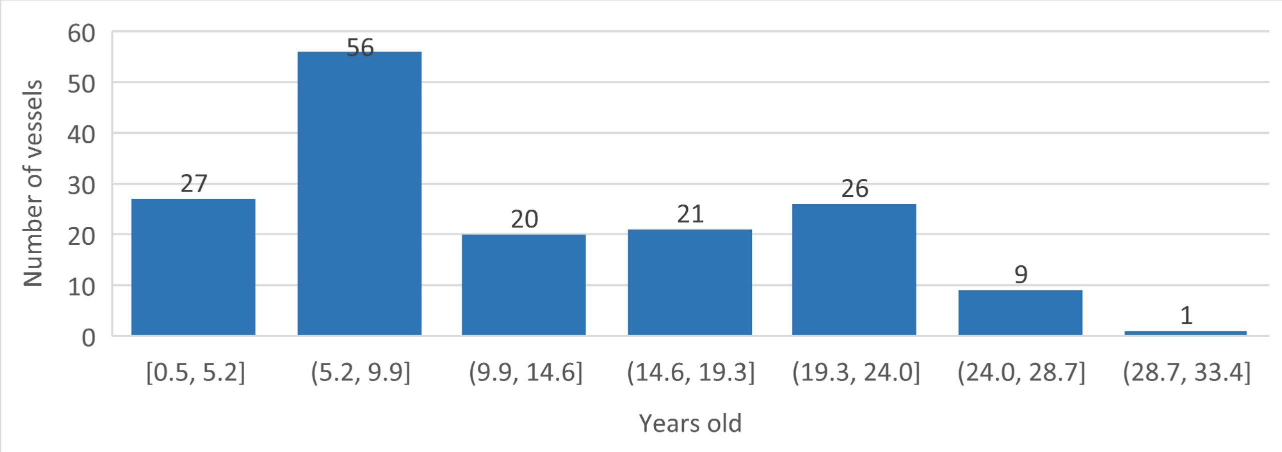

Figure 5. Histogram frequency (age group).

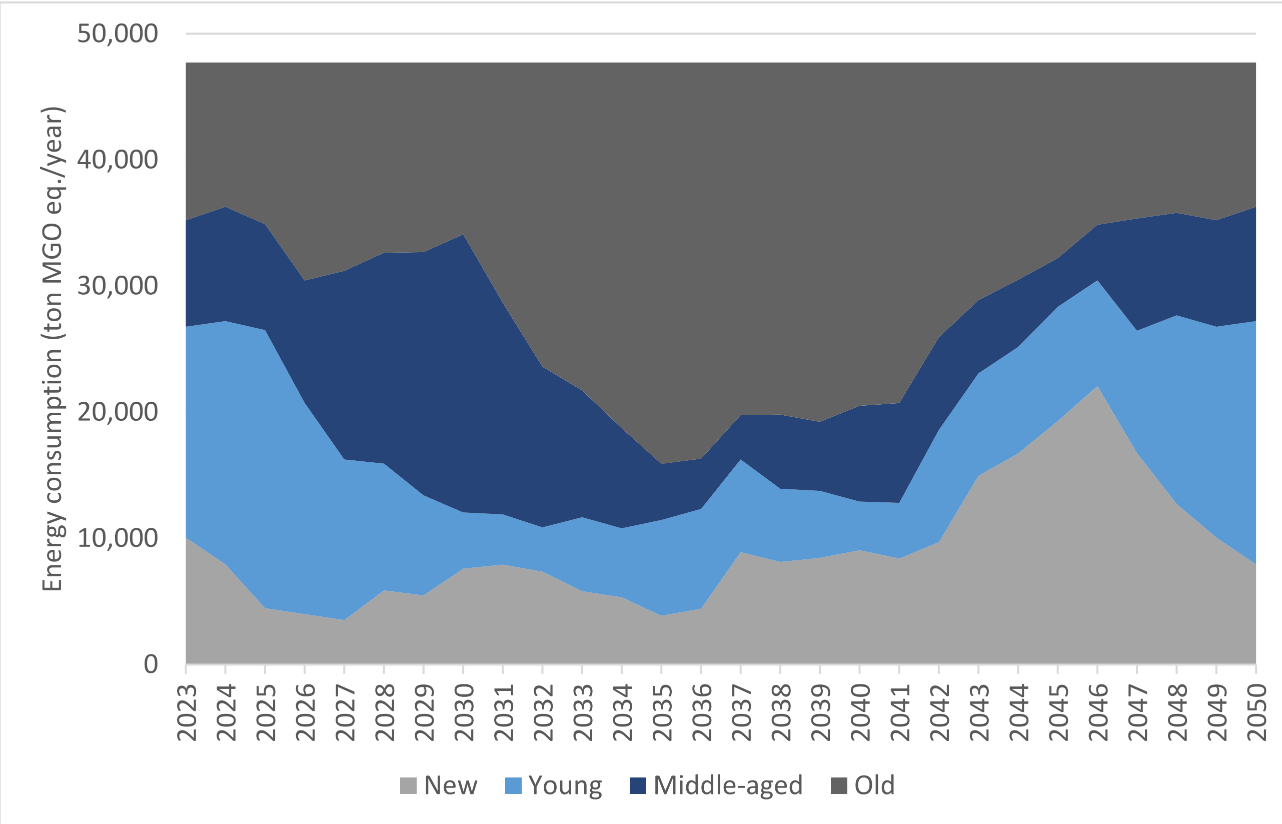

Figure 6. Energy consumption projection for age groups (new: <5 years; young: from 5 to 9.99 years; middle-aged: from 10 to 14.99 years; and old: from 15 to 30 years).

4.1.3. Energy Consumption, Speed, and Installed Power

Figure 7 shows that over 80% of the total energy is consumed by the large-tonnage group, driven by the high number of vessels in this category. The medium-tonnage group accounts for only 3% of the energy use, while larger vessels represent 16%. The Republic of Korea's domestic passenger vessel fleet consists mainly of small vessels and ferries, categorized by their engine power. There are three main categories: low power (0–1000 kW), with 30 vessels consuming 3997 tons of marine gas oil (MGO), medium power

(1000.1–5000 kW), with 110 vessels consuming 34,290 tons of MGO, and high power (over 5000 kW), with 20 vessels consuming 9434 tons of MGO.

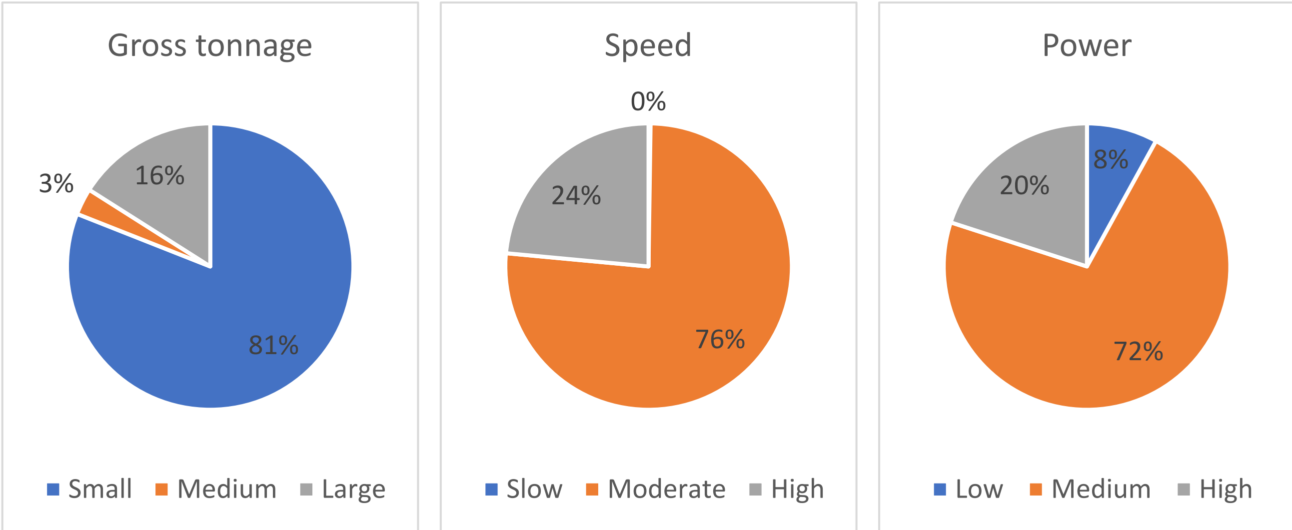

Figure 7. Energy consumption shares (gross tonnage: small—GRT < 1000; medium—GRT from 1001 to 5000; large—GRT > 5000; speed: slow at < 10 knots, moderate from 10 to 20 knots, and high from > 20 knots; engine power: low power: < 1000 kW; medium power: from 1000.1 to 5000 kW; and high power: > 5000.1 kW).

Medium-power vessels are the largest group, making up 72% of the fleet, while low-power vessels constitute 8% and high-power vessels account for 20%. There are only two slow-speed vessels below 10 knots, consuming 110 tons of MGO, which is negligible. In contrast, moderate-speed vessels traveling between 10 and 20 knots consist of 125 vessels, representing 76% of the fleet and consuming 36,389 tons of MGO. Additionally, 33 high-speed vessels exceeding 20 knots consume 11,223 tons of MGO, making up 24% of the total energy use.

4.2. Measures to Decarbonize

Table 3 below presents the maturity matrix of marine alternative fuels/energies and technologies for maritime decarbonization. It is expected that this matrix will be enhanced through the input of Korean experts, including ship designers, builders, and policymakers.

It is clear that operational measures can work well across all types of vessels in the domestic fleet. This shows an adaptable approach that recognizes the specific needs and operating conditions of each vessel category.

For small vessels, it is important to note that they have fewer options compared to larger vessels because of space restrictions. However, it is recommended that small vessels, especially those on short routes, effectively use battery or fuel cell technology to cut emissions. This focused approach takes into account the limitations of smaller vessels when suggesting practical ways to reduce emissions.

Larger and newly built vessels have many more options, ranging from operational improvements to alternative fuel technologies. These vessels can successfully incorporate both operational upgrades and alternative fuels to significantly reduce carbon emissions. Their flexibility and capacity make them ideal candidates for combining various measures to reach important decarbonization targets.

Table 3. Fuel and technology maturity matrix (color code: Score 1 (red)—not feasible/major challenges remain; Score 2 (yellow)—average/solution identified; Score 3 (green)—feasible/mature).

Categories	Measures	Size (Tonnage)			Age				Route			Speed		
		Small	**Medium**	**Large**	**New < 5**	**Young 6–10**	**Mid 11–20**	**Old > 20**	**Short**	**Mid**	**Long**	**Slow**	**Mid**	**High**
Ship Operation	Appropriate passenger planning	2.73	3.00	3.00	3.00	2.91	2.91	2.91	2.91	3.00	3.00	2.91	2.91	3.00
	Slow steaming	2.55	2.82	2.82	2.55	2.73	2.64	2.55	2.45	2.64	2.91	2.09	2.18	2.64
	JIT	2.73	2.82	2.91	2.82	2.91	2.91	2.73	2.64	2.82	2.91	2.91	2.91	2.91
	Trim and draft optimization	2.45	2.55	2.73	2.82	2.82	2.91	2.82	2.82	2.91	2.55	2.73	3.00	3.00
Technologies (Energy Saving) and Ship Design	WHRS	1.55	2.18	2.64	2.45	2.64	2.00	1.64	1.82	2.36	2.64	2.27	2.18	2.64
	Air lubrication systems	1.73	2.18	2.64	2.91	2.91	2.36	1.64	2.09	2.45	2.73	2.36	2.45	2.64
	Hull coatings	2.91	2.91	2.82	2.91	2.91	2.64	2.18	2.64	2.91	2.91	2.82	2.91	2.91
	Hybrid power systems	2.27	2.27	2.36	2.64	2.18	1.91	1.45	2.64	2.45	2.45	2.45	2.27	2.18
Alternative Fuels	Ammonia	1.55	1.73	1.73	1.82	1.45	1.18	1.18	1.82	1.82	1.64	1.64	1.64	1.64
	Biodiesel/biofuels	2.45	2.36	2.09	2.45	2.45	2.09	1.73	2.45	2.36	2.09	2.45	2.45	2.45
	Hydrogen/fuel cells	2.55	2.27	1.55	2.55	2.00	1.64	1.27	2.73	2.27	1.55	2.55	2.36	2.27
	LNG	1.82	2.18	2.45	2.55	2.09	2.00	1.45	2.36	2.36	2.45	2.18	2.64	2.64
	Methanol	1.82	2.27	2.45	2.55	2.18	1.82	1.18	2.18	2.27	2.18	2.27	2.45	2.45

It is worth mentioning that the use of ammonia and hydrogen internal combustion engines (H2 ICEs) is not recommended based on expert evaluations. Instead, the focus is on solutions like hull coatings and JIT strategies, which are preferred for their effectiveness at lowering emissions.

For older vessels, which have fewer options due to their age, targeted actions such as small retrofitting measures are suggested. These actions consider the limitations of older vessels while striving to improve their efficiency and cut emissions. By emphasizing measures like hull coatings and just-in-time arrival, even older vessels can see gradual improvements in their decarbonization efforts.

While this study primarily focuses on proposing a decarbonization roadmap, future research could explore detailed case studies or simulation experiments to evaluate the implementation and effectiveness of these measures in practical applications.

4.3. Future Fleet Emission Projection

Projections for future GHG emissions from the domestic fleet were constructed on the basis of the GHG intensity analysis described in Section 4.1. The analysis investigated the GHG reductions in scenarios focusing on four different energy carriers, as shown in the list below:

- Scenario 1: increased utilization of fossil fuels;
- Scenario 2: enhanced integration of biofuels;
- Scenario 3: greater adoption of battery technology and electricity;
- Scenario 4: expanded usage of hydrogen and ammonia as alternative fuels.

The GHG intensity projection scenarios for the future fleet were constructed using the GHG intensity levels predicted for an energy mix with a particular emphasis on one of the above energy carriers. The fraction of energy derived from one particular energy carrier varied at two discrete levels as 50% and 80%, and other energy carriers provided the remaining energy. The exact distribution of the energy share provided by each energy carrier in each scenario is provided in Tables 1 and 2.

The feasibility of meeting the national targets for reductions in GHG emissions for domestic shipping in the Republic of Korea [4], as presented in Figure 1, was investigated for each of these scenarios. The aim was to reduce the total GHG emissions to 60% by 2030, to 45% by 2040, and to 30% by 2050.

The results showed that if the emphasis on one energy carrier is applied with a 50% energy share emphasis, then the only scenario that is not expected to be able to meet the 2030 target of reducing GHG emissions to 60% is the fossil fuel scenario, which assumed a continued use of 50% of the fleet energy from unabated fossil fuels. In this case, 20% of the fleet energy was assumed to come from MGO, and 30% from LNG. The scenarios with a 50% energy share emphasis on biofuels, battery–electric propulsion, and hydrogen and ammonia were all able to meet the 2030 and 2040 targets of reducing GHG emissions from the fleet to 60% and 45% of their 2018 level (Figure 8).

The 2050 scenario of reducing fleet GHG emissions to 30% from their 2018 level can only be met by the use of hydrogen and ammonia if the emphasis on one energy carrier is applied with a 50% energy share emphasis. It should be noted here that for hydrogen and ammonia, it was assumed that these fuels were produced from renewable electricity, whilst it was assumed that the battery–electric propulsion was charged with the electricity of the energy-specific carbon intensity of the electricity supply in the Republic of Korea (assumed to be 180 g CO_2 eq./kWh [53]). If the energy-specific carbon intensity of the electricity supply can be reduced, this would positively affect the results for the scenario with an emphasis on battery–electric propulsion.

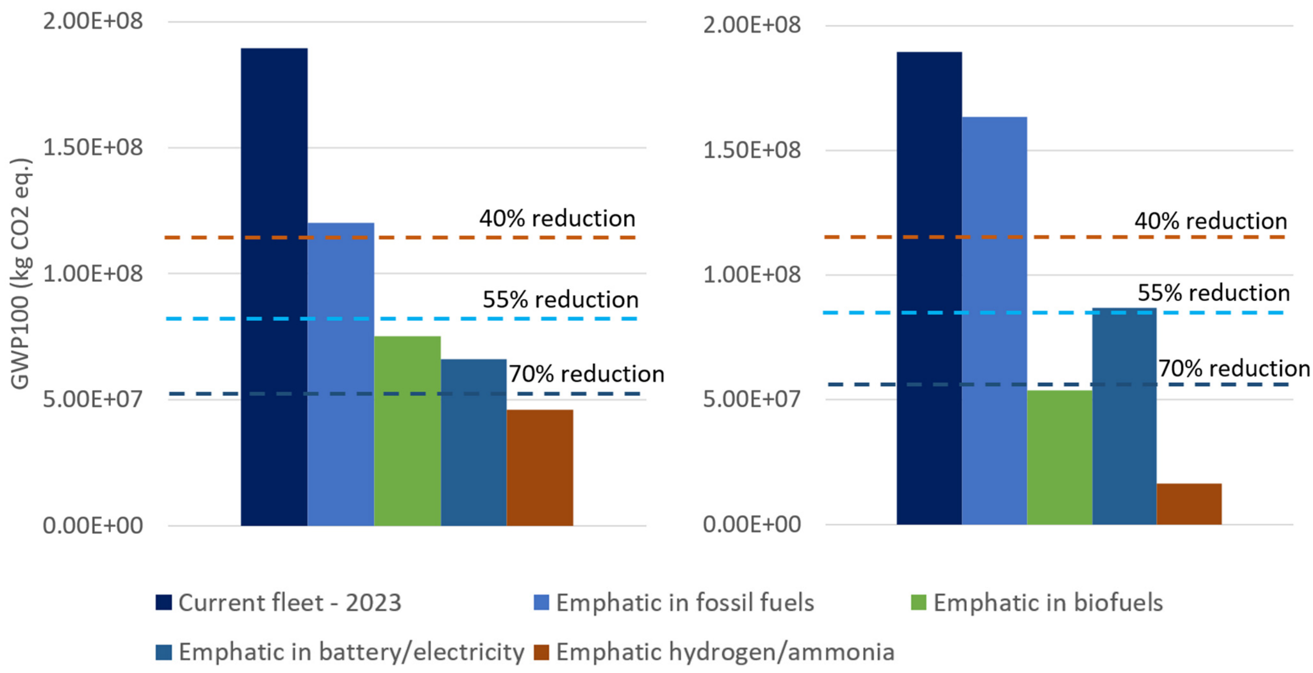

Figure 8. Future fleet projection for domestic fleet under different scenarios: the 50% scenario (**left**) and 80% scenario (**right**).

In the case of the emphasis on one energy carrier being applied with 80% of the total energy share of the fleet, the GHG reduction potential was higher for the biofuel, hydrogen, and ammonia fuel cases, but it was lower for the fossil fuel case and the battery–electric case that assumed an electricity GHG intensity of 180 g CO_2 eq./kWh. For the case of biofuels, the 2050 emission reduction target was just within reach by providing 80% of the fleet energy supply from biofuels. This not only shows the value of biofuels during the earlier stages of a greenhouse gas reduction transition, but it also highlights the limitations of reaching values close to net-zero GHG emissions. Achieving further reductions in GHG emissions with biofuels will likely require the use of carbon capture techniques, such as bioenergy use with CCS (BECCS), in order to achieve net-zero or even negative GHG emissions. Synthetic carbonless fuels such as hydrogen and ammonia were shown to be most effective at reaching very low GHG emissions levels below 30% of the 2018 level, without any additional carbon capture and storage (CCS). By implementing a fleet energy of 80% from hydrogen and ammonia, the fleet could reach GHG emission levels below 10% of the current level.

The levelized cost for operating the entire fleet for one year, including the energy cost and emission cost, was analyzed for each of the scenarios by also including a cost for GHG emissions, set at \$230/tCO_2 eq. [52]. This levelized cost of one year of fleet operation included the influence of the capital investment required and the operational expenses, and it factored in the costs for the end-of-life recycling of the vessel. The results are shown in Figure 9 for all scenarios with a 50% or 80% emphasis on one particular energy carrier. The results show that the levelized costs were relatively similar for all scenarios, with the lowest costs attributed to the biofuel scenario and the highest costs associated with the scenario with an emphasis on battery–electric propulsion. The total levelized cost variations lay within 20% of one another, but the fractions of the costs associated with the cost of energy and the cost of GHG emissions varied.

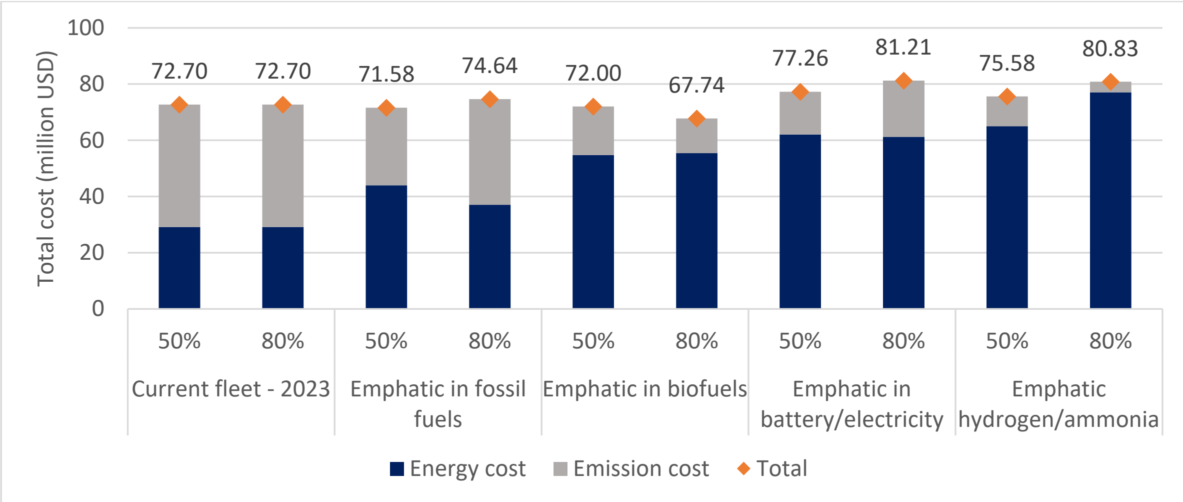

Figure 9. Levelized operating costs for fleet under different energy scenarios.

The current fleet and the scenario with an emphasis on fossil fuels had the largest share of their costs associated with GHG emissions from their operations, whilst the scenarios with an emphasis on hydrogen and ammonia produced from renewable resources had the lowest cost associated with GHG emissions from their operations but the highest costs associated with the implementation of the technology. These results highlight that internalizing the GHG emission cost using a suitable GHG levy, in this case set at KRW 230/tCO_2 eq. [52], can level out the economic competitiveness between the various energy carrier options.

The GHG abatement cost was calculated for each scenario, based on the reduction in GHG emissions and the respective costs. The GHG abatement costs for the scenarios with an emphasis on biofuels, battery–electric propulsion, and hydrogen and ammonia fuels can be seen in Figure 10.

The results show that biofuels offer the lowest abatement costs for GHG reductions, whilst the highest abatement costs were found for battery–electric propulsion. The synthetic carbonless fuels hydrogen and ammonia provided intermediate GHG abatement costs.

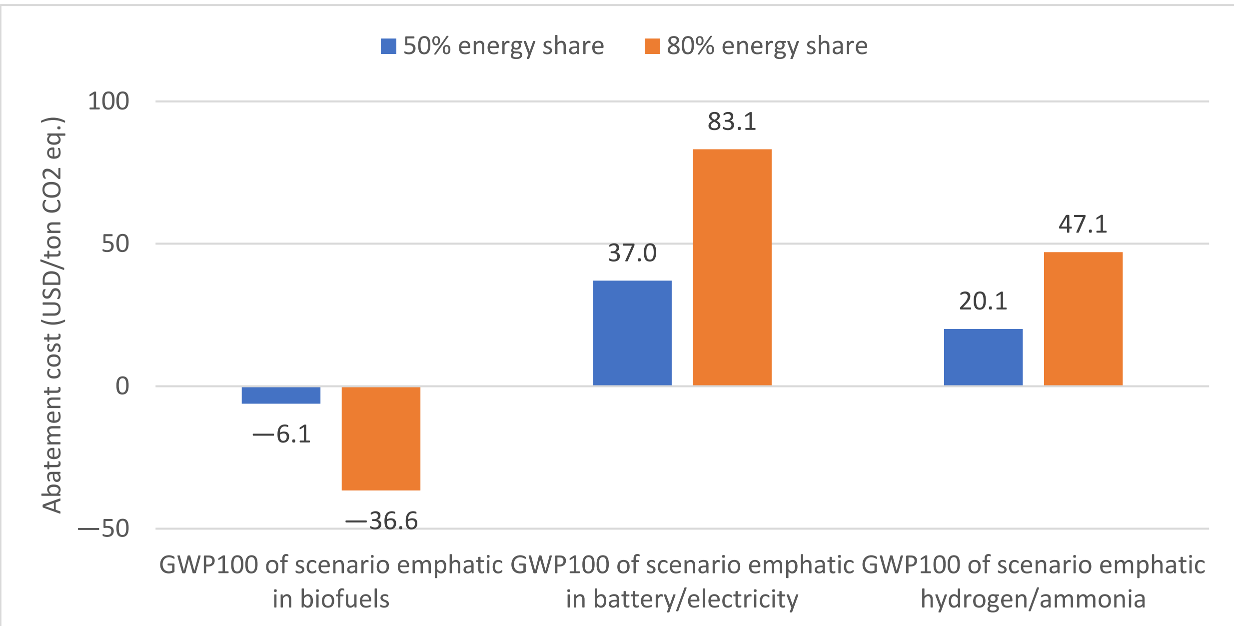

Figure 10. GHG abatement costs for different decarbonization scenarios.

4.4. Roadmap for Decarbonization

Table 4 indicates that prioritizing fossil fuels will not align with the national emission reduction targets for 2030, 2040, or 2050. This implies that the proportion of fossil fuels will need to be reduced to below 50% by 2030 if the fleet is to maintain its current operational speed without implementing additional energy efficiency measures. Achieving this reduction in fossil fuel usage to below 50% by 2030 presents significant challenges. Therefore, operational energy efficiency measures will likely be crucial in meeting the goal of a 40% reduction in GHG emissions by 2030, as emphasized in the literature review in Section 2.

Table 4. Assessment of various scenarios for achieving the 2023 emission reduction target set by the Ministry of Oceans and Fisheries for domestic shipping in the Republic of Korea (**X**—no longer applicable for maritime decarbonization; **?**—current solutions are not yet viable; √—promising potential solutions are emerging).

Targets	Fossil		Biofuels		Electrification		Hydrogen/Ammonia	
	50%	80%	50%	80%	50%	80%	50%	80%
2030 40% GHG reduction	X	X	√	?	?	?	√	√
2040 55% GHG reduction	X	X	√	√	√	X	√	√
2050 70% GHG reduction	X	X	X	√	X	X	√	√

Figure 11 below shows the proposed decarbonization roadmap for the South Korean fleet. The roadmap sketches out the technological solutions (above the arrow) and the necessary implementation pathways (below the arrow) to decarbonizing the domestic shipping fleet through short-, medium-, and long-term measures. In the **short term** (by 2030), the focus can be on employing hybrid and electric propulsion systems, particularly for small vessels, and alternative fuels like biodiesel, LNG, and methanol. The main priorities entail improving the energy efficiency and deploying easily available solutions, for instance, propulsion-improving devices and wind-assisted propulsion. Investing in renewable energy is also a central step to guarantee that the electricity used for hybrid systems achieves the decarbonization targets. Still, to successfully implement these technologies, **a number of pathways** must be employed, including raising the awareness of maritime stakeholders and training and educating seafarers and operators to adopt new technologies, including the adaptation to the IMO EEDI, EEXI, and CII for domestic ships. Policymakers also need to reinforce this shift through incentives, subsidies, and decarbonization regulatory frameworks.

In the **medium term** (2030–2040), transitioning to low- or zero-carbon fuels, such as green methanol and biodiesel, will be essential. The current hybrid systems may be phased out as their economic and operation lifespans finish, and there is a greater focus on lifecycle emissions. **Implementation pathways** will focus on policies promoting green technologies and market-based measures such as carbon pricing or emission trading schemes, including the integration of and improvement in the capabilities of green corridors to support the industry's decarbonization.

By the **long term** (2040–2050), the roadmap envisions the renewal of much of the fleet, equipping new vessels with low-carbon technologies. Hydrogen is expected to become more dominant, and the focus will shift to fully renewable energy sources, including solar power, to achieve the IMO's net-zero emission targets by 2050. The **implementation strategies** will need to advocate the capture of renewable energy in both ship design and operations. Furthermore, government support is required to make sure that green hydrogen is fully integrated into the maritime industry, aligning with South Korea's comprehensive green advancement and decarbonization goals.

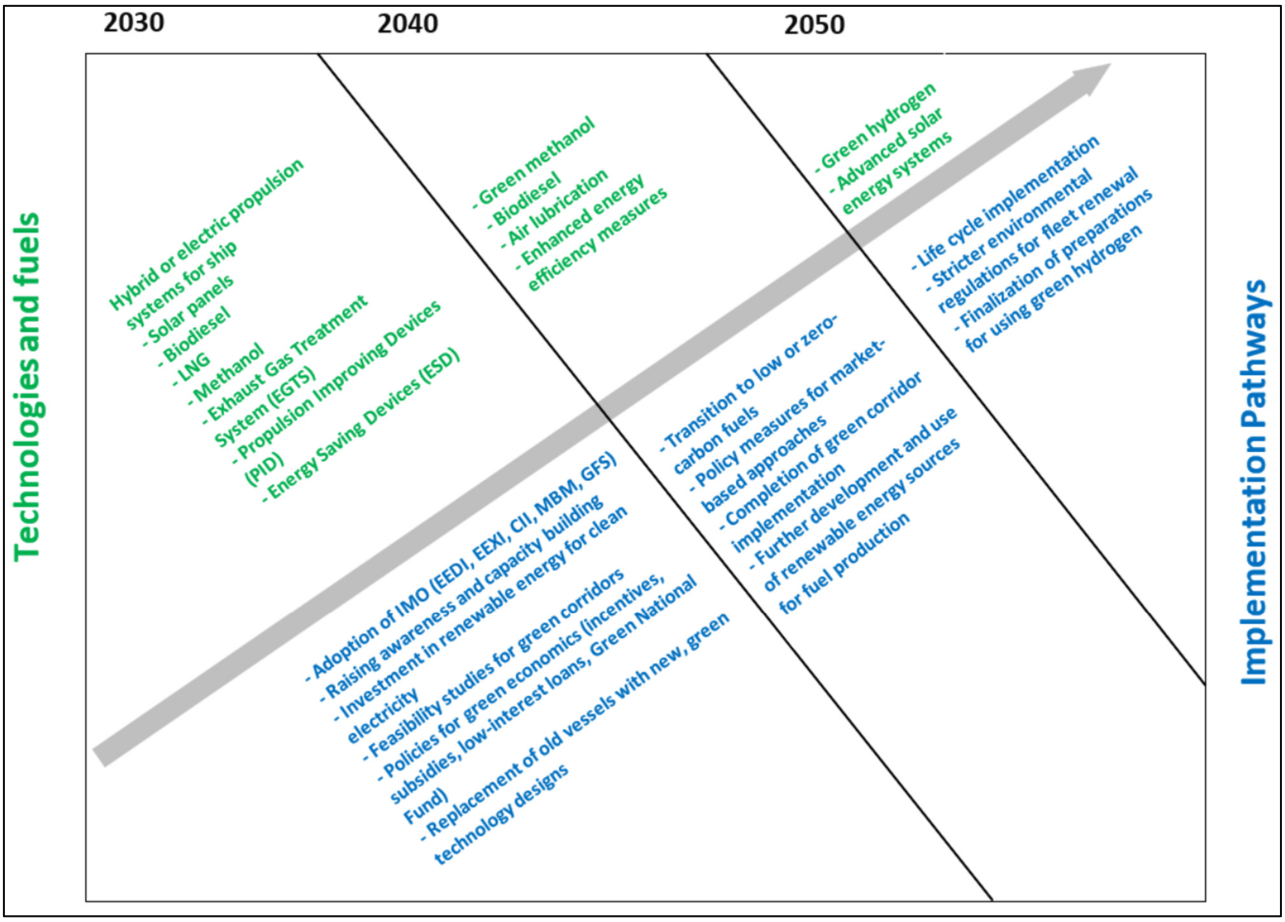

Figure 11. Roadmap for decarbonizing the domestic passenger ferry fleet in South Korea.

5. Conclusions

This research outlines a proposed roadmap for decarbonizing the domestic passenger ferry fleet in the Republic of Korea. A variety of research methods were employed, including data collection and analysis, the exploration of potential maritime technologies, projections for the future fleet, and expert validation. Based on these analyses, the roadmap was formulated.

In analyzing the domestic passenger ferry fleet of the Republic of Korea, detailed data on the vessel types, fuel usage, and emission levels were gathered and assessed. The total emissions from the fleet were calculated, showing that most emissions come from the use of fossil fuels, with CO_2 being the largest contributor. This analysis gave us a clear picture of the fleet's current environmental impact, pointing out areas where improvements can be made.

To facilitate emission reduction, various decarbonization measures were explored, including the use of alternative fuels like biofuels and hydrogen, as well as efforts to improve the operational efficiency and technology. The results indicate that these combined strategies could lead to significant emission reductions. Looking at future projections, it was found that focusing on hydrogen and ammonia as fuel options offers the best chance to meet the national goal of a 40% reduction in greenhouse gases by 2030, highlighting the fleet's potential to support Korea's environmental targets.

The roadmap's implementation will significantly benefit stakeholders, including ship operators, government agencies, and port authorities, by reducing costs, meeting environmental regulations, and supporting innovation. Modernized facilities and clean technologies will help South Korea maintain its competitiveness while achieving its decarbonization targets.

However, challenges like high upfront costs and limited infrastructure for alternative fuels remain. Further studies are also needed to assess the scalability of green shipping corridors and the integration of renewable energy into the maritime sector. Collaboration with industry stakeholders and policymakers will be critical to overcoming these challenges and ensuring practical and scalable decarbonization strategies. Collaboration with industry stakeholders will ensure practical and effective steps toward South Korea's ambitious decarbonization goals. Additionally, the strategies and findings presented in this roadmap can be adapted to other regions with similar fleet characteristics and decarbonization targets, offering a broader application beyond South Korea.

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