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Simulation Method of Decarbonization of International Shipping for Evaluating the Impact of Possible Regulation Limiting GHG Intensity of Marine Fuels

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ABSTRACT

This study explored how the GHG fuel standard (GFS) regulation affects international shipping quantitatively by simulating future fleet transformation, fuel consumption, and well-to-wake GHG emissions based on an inputted GHG fuel intensity pathway and scenario of transportation demand, fuel availability and costs, and technology availability. The method comprises three steps: calculating the amount of scrapped and built ships, allocating fuel type and mix, and calculating fuel consumption. We simulated how the regulation changes fleet composition and the mix of fuel consumption. From the perspective of feasibility and alternative fuels' availability, some meaningful insights to implement the GFS regulation were delivered.

KEYWORDS

Simulation of fleet transformation; GHG fuel standard; Decarbonization of shipping.

INTRODUCTION

In 2023, the International Maritime Organization (IMO) revised its GHG reduction strategy to include net-zero emissions by 2050 (IMO MEPC, 2023). The strategy includes targets for introducing green fuels and total emission reduction, that is, the indicative checkpoints. These checkpoints were set for 20-30% and 70-80% reduction by 2030 and 2040 respectively. However, the technology to achieve decarbonization is in the R&D stage and has not yet been established. Although various fuels have been studied as marine fuels such as ammonia (Kim et al, 2020; Inal et al., 2022), biofuels (Tan et al. 2022), eMethane, eMethanol, and hydrogen (Shi et al., 2023), it remains undetermined which fuels and energy sources will be used in international shipping (Balcombe et al., 2019) and the fuels' availability is highly limited (Grzelakowski et al., 2022).

To encourage technological and infrastructure development to achieve this goal, various regulations, including technical and economic elements, are being discussed by the IMO. As for the economic elements, market-based measures (MBM), such as feebate and carbon levy, are being considered (Psaraftis, 2021), and the impact and implementation of these measures have been studied. For example, Wang et al. (2015) developed an economic model and evaluated the emission-trading scheme (ETS). They compared open-ETS and maritime-only ETS and discussed the economic impacts on container and bulkcarrier shipping. Metzger (2022) evaluated the impact of carbon pricing on the valuation of investments in

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greening technologies using the fuzzy pay-off method. Masodzadeh et al. (2022) discussed MBM complications and proposed a new hybrid MBM to fill the gap between short-term measures and the MBM.
However, mid-term technical measures, such as the GHG fuel standard (GFS) have not yet been studied. The GFS is a regulation that requires ships to use fuels with well-to-wake (WtW) GHG intensity (gCO_2eq/MJ) below the defined limit called the GHG fuel intensity (GFI) (IMO, 2021). A similar regulation will be introduced in FuelEU Maritime (ClassNK, 2023), which is a local regulation to be introduced in EU/EEA Member States in 2025. The framework is considered to be a certain promise, and the impact should be evaluated before implementation. When discussing the GFS, one of the important issues is whether to introduce a flexibility mechanism that allows the ships to share their GHG emission reductions in the fleet. Without this mechanism, all ships must individually comply with the GFS. However, with the flexibility mechanism, ships using better fuel than the required GFI can provide a surplus to ships that cannot comply with the required GFI. This means that the overall fleet complies with the regulations. As the path to shipping decarbonization varies depending on whether the mechanism is introduced, the impact of the flexibility mechanism must be evaluated. Moreover, the IMO's indicative checkpoints are based on total emissions from the fleet, and a macro analysis of the fleet is necessary to determine whether the GFS adequately contributes to the IMO's target.
Modeling and simulation are powerful tools for quantitatively evaluating the impact of future regulations. Eide et al. (2011) built a model to assess the cost and GHG reduction of various measures by combining a fleet projection model with activity-based CO_2 calculations and evaluated the amount of GHG reduction and the required cost by using the marginal abatement cost curve (MACC). Halim et al. (2018) developed a future CO_2 estimation model combining the International Freight Model and Activity, Structure, Intensity, and Emission factor methods and conducted impact assessments of various GHG reduction measures until 2035. Wada et al. (2021) used system dynamics to model the shipping and shipbuilding market and forecast future shipbuilding demand affected by the EEDI, slow steaming, and penetration of LNG to reduce GHG emissions. Zwaginga et al. (2022) pointed out that future uncertainties including regulation make designing ships difficult and utilized three methods to deal with the deep uncertainty in designing alternative fueled ships: dynamic adaptive policy pathways (DAPP), responsive system comparison (RSC), and robust decision making (RDM). By comparing the three methods, it demonstrates what insight could be obtained and how the ship design is affected by the uncertainties. However, a simulation method that can model GFS regulation and analyze its behavior, to the best of our knowledge, has not yet been developed.
The objective of this paper is to study how the GFS regulation affects international shipping in the future, and a simulation method is proposed for this purpose. The simulation projects future fleet transformation, fuel consumption, and well-to-wake (WtW) GHG emissions based on an inputted GFI pathway and enables us to study the regulation quantitatively from the perspective of feasibility, fuel, technology availability, and so on. In the case study, we assumed a GFI pathway considering the revised IMO GHG reduction strategy and simulated several cases with and without the flexibility mechanism. By comparing these results, we have analyzed how international shipping is affected by the presence or absence of the flexibility mechanism. Moreover, another case shows how the simulation can be used to search for GFI pathways that are feasible and contribute to GHG reduction as much as possible and demonstrates that the proposed method can support the design of the GFS regulation.

SIMULATION METHOD

Overview of the Method

Figure 1 shows an outline of the proposed simulation method, which consists of three parts: a model of shipbuilding and scrapping, a model for selecting the introduced ships and calculating the fuel mix, and a calculation of fuel consumption. The proposed method requires fleet composition data that defines the initial fleet status and five scenarios as follows: transportation demand, ships' survivor rate to age, GFI pathway that defines how WtW emission regulation in the simulation will be tightened, ship data including ships using alternative fuels, and fuel data including costs, emission factors, and availability. In this simulation, the GFS is defined by the GFI pathway, and ships and fuels are operated on the assumption that the GFI is not exceeded. The figure describes what data and scenarios are required for each part, and what kind of output is produced by the part. The simulation flow is run iteratively from 2021 to 2050 with a timestep of one year and outputs WtW emissions, WtW GHG intensity (gCO_2eq/MJ), and costs including those of fuel and ship. In addition, the amount of shipbuilding and scrapping, the ships' fuel type introduced at each time step, and the fuel mix utilized for the operation were considered. The remainder of this section explains the data and calculation procedures for each part.

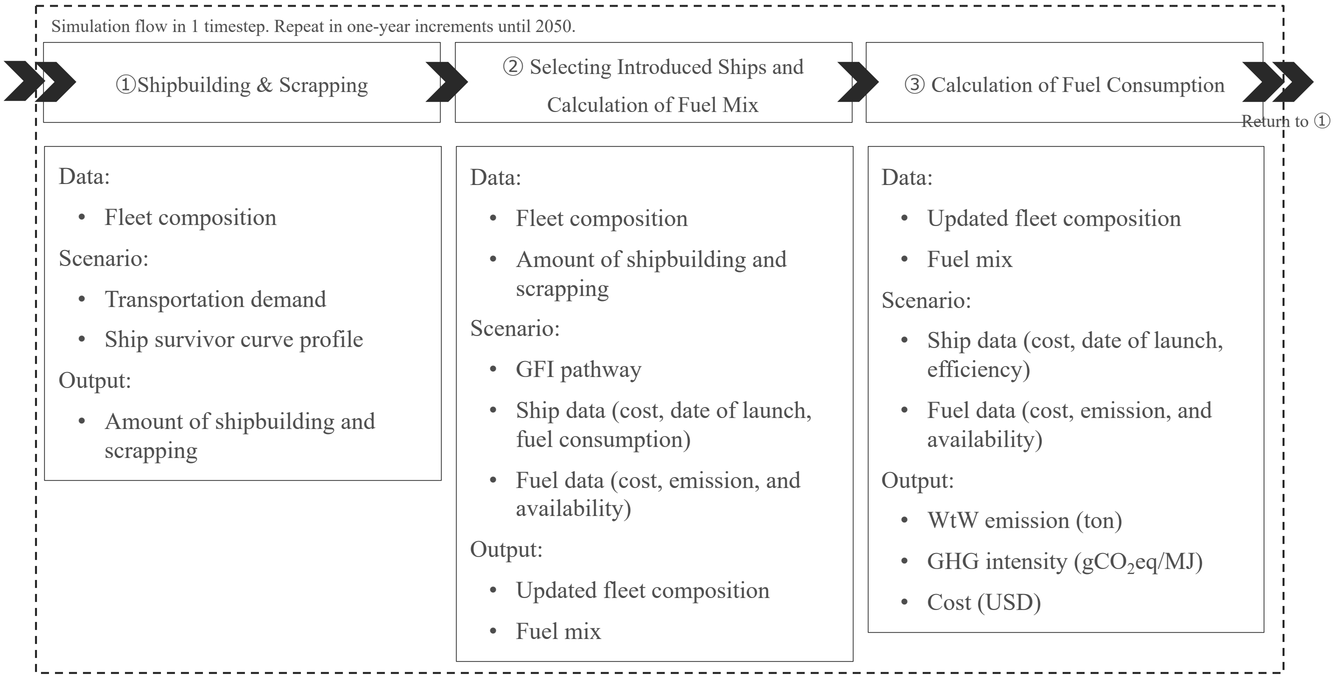

Figure 1: Outline of the proposed simulation flow

Models of Shipbuilding and Scrapping

As for the model of shipbuilding and scrapping, the method assumes that shipbuilding is related to transportation demand, and the amount of scrapping is related to ship age distribution. First, the amount of scrapping was calculated based on fleet composition data defined by age, ship type, and the number of ships. The number of ships scrapped $Scrap_{t,a}^{type}$ is shown in equation 1. The fleet data are represented by $Ship_{t,a}^{type}$, which indicates the number of ships whose age is a and ship type is $type$ at time t. $Sr(a)$ is the survivor rate at the ship age. The ship type is a label indicating the fuel that the vessel can use, such as LNG, NH_3, and Methanol. Note that the fuel type in the method mentioned afterward is a more detailed fuel label such as eAmmonia(Blue), eAmmonia(Green), and so on, and is different from the ship type. Ship type defines a set of fuels that can be utilized. This is described in more detail in the "Case Study" section.

$$Scrap_{t,a}^{type} = Ship_{t,a}^{type} \cdot (1 - Sr(a+1)/Sr(a)) \tag{1}$$

The number of newly built ships was calculated by adding the number of new buildings to meet the growth in transportation demand to the amount of scrapping calculated by Equation 1. The number of newly built ships B_t is calculated by Equation 2.

$$Built_t = \sum_{type}\sum_{a} Scrap_{t,a}^{type} + \sum_{type}\sum_{a} Ship_{t,a}^{type} \cdot (1 - Transportwork_{t+1}/Transportwork_t) \tag{2}$$

$Transporwork_t$ is the amount of transport work (billion-ton mile) that is supposed to be transported by the fleet at time t. Through this process, the amount of scrapping for each ship type and age and the amount of shipbuilding for the fleet are calculated. Because the objective of this method is to analyze the regulation's behavior from a macro perspective, the fleet is represented as a set of averaged vessels with no distinction between cargo and size, and the average size of the vessels is constant in the future.

Model of Selecting Introduced Ships and Calculation of Fuel Mix

In this subsection, a model is used to select the ship types that will be built for the shipbuilding volume calculated in the previous step and to calculate the fuel mix consumed by the fleet in the next time step. The process differs in the GFS with and without the flexibility mechanism. First, the model in the case without the flexibility mechanism is explained, followed by the differences in the case with the mechanism.

Without the flexibility mechanism, each ship in the fleet complies with the regulations and does not share the emission reductions. The model for selecting the introduced ship types and calculating the fuel mix consists of four steps: take n types of ships from the set of ship types that can be introduced and create a list of combinations of these types a pre-defined share rate, optimize the fuel mix in the fleet as each combination is introduced, and extract the combination with the lowest cost among all combinations. The ships to be introduced are selected according to their costs, including ship and fuel cost. The details of the equation in the optimization are as Equations 3 – 8, where FU_{fuel}^{type} is the percentage of fuel mix used by a specific ship type, is DFC is fuel consumption (MJ) by a ship in 1 year, $Ship_t^{type}$ is the number of ships whose type is $type$, FP_{fuel} is fuel cost(USD/MJ), SP_{type} is ship cost (USD), CI_{fuel} is carbon intensity (gCO_2eq/MJ) of each fuel, GFI is a defined GFI value for the regulation, $Limit_{fuel}$ is the fuel's availability (MJ), $FUEL$ is the set of fuel being calculated, and $SHIP$ is the set of ship types defined in the simulation.

$$\min \sum_{type} \left(\sum_{fuel} FU_{fuel}^{type} \cdot DFC \cdot FP_{fuel} + \frac{1}{20} SP_{type} \right) \cdot Ship_{t+1}^{type} \tag{3}$$

s.t.

$$\sum_{fuel} FU_{fuel}^{type} \cdot CI_{fuel} \leq \frac{GFI}{100} \cdot CI_{LSFO} \tag{4}$$

$$\sum_{type} FU_{fuel}^{type} \cdot DFC \cdot Ship_{t+1}^{type} \leq Limit_{fuel}, \forall fuel \in FUEL \tag{5}$$

$$\sum_{fuel \in MAIN, PILOT} FU_{fuel}^{type} = 1, \forall type \in SHIP \tag{6}$$

$$\sum_{fuel \in MAIN} FU_{fuel}^{type} \leq 1 - pfr, \forall type \in SHIP \tag{7}$$

$$\sum_{fuel \in PILOT} FU_{fuel}^{type} \geq pfr, \forall type \in SHIP \tag{8}$$

Equation 3 represents the objective function to be minimized, which is the total cost including the fuel cost and the ship cost. As for the ship cost, the value is depreciated over 20 years. Equations 4 and 5 represent constraints, respectively, to comply with the regulation, and of fuel availability. Equations 6-8 are constraints around fuel usage. $MAIN$ is the set of fuels primarily used on the ship, and $PILOT$ is the set of pilot fuels. For example, in a dual-fuel ship of LNG, LNG, eMethane, and BioMethane are primarily used, and LSFO and bio-heavy fuel oil (BioHFO) are used as pilot fuels. pfr is the pilot fuel rate required to operate; in the simulation, it is defined as 0.05 until 2040 and 0.03 thereafter.

In the case with the flexibility mechanism, ships in the fleet can share their emissions to comply with the regulation so that Equation 4 in the optimization differs as shown in Equation 9.

$$\sum_{type} \sum_{fuel} FU_{fuel}^{type} \cdot CI_{fuel} \cdot Ship_{t+1}^{type} \leq \frac{GFS}{100} \cdot CI_{LSFO} \cdot \sum_{type} Ship_{t+1}^{type} \tag{9}$$

All possible combinations are optimized, and ships with the lowest minimized cost are selected for construction. For the calculation, it is necessary to determine the number of types of ships that will be introduced in the future and the market share of these types. To simplify the calculation, we assume that three types of ships have constant market shares of 50%, 30%, and 20%, respectively. Although it is difficult to establish the market situation in the future, the authors interviewed multiple shipping companies in Japan and developed the above-mentioned assumptions. This step outputs

the types of newly built ships and the percentage of fuel utilized by each type of ship in the fleet. Once the type of newly built ships is determined, the updated fleet composition for the next year's operation can be calculated.
When using the model, depending on the input GFI pathway and fuel availability scenario, no optimization solution may exist, which means that the input GFI pathway cannot be complied with by the scenario. In this case, to continue the calculation, the constraint on the GFI is removed (Equation 4) and a penalty for emissions is added to the objective function. This minimizes costs and emissions. As for the penalty, this simulation applied the penalty of FuelEU Maritime, which is calculated by multiplying the energy consumption that exceeds the regulation value by 0.06 EUR/MJ.

Calculation of Fuel Consumption

The fuel consumption is calculated based on the updated fleet composition and fuel mix obtained in the previous step. After calculating the fuel consumption, the WtW emissions, WtW GHG intensity, and costs were calculated. Equations 10–13 represent the calculation, where FOC_{fuel} is the fuel consumption (MJ) of each fuel, FU_{type}^{fuel} is the fuel mix used by a specific ship type, $Emission_{WtW}$ is WtW emissions (ton), $Emission_{intensity}$ is a the GHG intensity of the fleet normalized by the LSFO's intensity, and $FuelCost$ is the fuel cost of the fleet. The consumption of each fuel is calculated by multiplying the fuel mix, average fuel consumption per ship, and the number of ships. Because there are fuels that can be used in multiple ship types, such as LSFO, aggregation by ship type is performed. In the output cost data, CAPEX is added to the fuel cost as the total cost. For the CAPEX, only the ship cost is considered and 1/20 of the total ship cost is accounted for, assuming that the depreciated period is 20 years.

$$FOC_{fuel} = \sum_{type} FU_{type}^{fuel} \cdot Ship_{t+1}^{type} \cdot DFC \quad [10]$$

$$Emission_{WtW} = \sum_{fuel} FOC_{fuel} \cdot CI_{fuel} \quad [11]$$

$$Emission_{intensity} = \sum_{fuel} (FOC_{fuel} \cdot CI_{fuel})/(CI_{LSFO} \cdot \sum_{fel} FOC_{fuel}) \quad [12]$$

$$FuelCost = \sum_{fuel} FOC_{fuel} \cdot FP_{price} \quad [13]$$

CASE STUDY

Overview and Scenarios

This case study aims to demonstrate how the proposed method of this paper evaluates the GFS, and what kind of insight can be delivered. In this paper, two cases are conducted. In Case 1, a comparison of the GFS with and without the flexibility mechanism was conducted. When the GFS is applied without the flexibility mechanism, all vessels should align with the GFI pathway. However, when the GFS with the flexibility mechanism is applied, not all vessels need to align with the GFI pathway, rather, the GFI pathway should be achieved at the fleet level. The comparison demonstrates that the proposed method enables a quantitative evaluation of the advantages of the flexibility mechanism. In Case 2, a GFI pathway that achieves as much decarbonization as possible and does not have much impact on the shipbuilding market is explored in a more severe scenario. The GFI pathway to achieve IMO's indicative checkpoint depends on the transportation demand scenario, and the higher the transportation demand, the more stringent the GFI pathway should be set. However, setting too stringent a GFI pathway would make it difficult to adapt to existing HFO vessels and would greatly reduce the regulation's feasibility. If existing vessels cannot be adapted, conversion or replacement can be considered; however, too much conversion or replacement will have a significant impact on the shipbuilding market. In Case 2, we input several GFI pathways, and explore which pathway can best lower GHG emissions and does not require conversion or replacement.
The remainder of this subsection summarizes the scenarios of transportation demand, fuels, and ships used in the case study.

Ship scenarios
In this case study, 32275 vessels with a gross tonnage of 5000GT or more that operate worldwide were set as the initial fleet. The dataset is based on the IHS Sea-web (S&P Global, 2023), which is the largest web-based ship database service and is generated by excluding offshore-related ships, tugs, barges, and patrol ships from all vessels listed in the database. In this case study, ships of various cargoes and sizes are averaged, and the fleet is represented only by the number of ships, ship age, and ship type. Figure 2 shows the initial fleets' age distribution. To calculate the fuel consumption and emissions, it is necessary to define the average fuel consumption per ship, which is defined as 2.85×10^8(MJ) in this case study. This setting is based on the IEA reporting that energy consumption in international shipping in 2022 is 9.2 (EJ) in total (IEA, 2023). Fuel consumption will be improved in the future because energy efficiency regulations such as EEDI and EEXI are applied, and to align the regulations, propulsion technology is refined. In this case study, based on fuel efficiency in 2008, the. efficiency would improve by 22%, 40%, and 50% in 2018, 2030, and 2050, respectively. This assumption is based on the 4th IMO GHG Study (Faber et al, 2020) and the IMO GHG reduction strategy adopted in 2018(IMO, 2018). The 4th IMO GHG Study reported a 22% improvement in the annual efficiency ratio in 2018 compared with that in 2008, and the reduction strategy adopted in 2018 targeted a 40% improvement in energy efficiency by 2030.

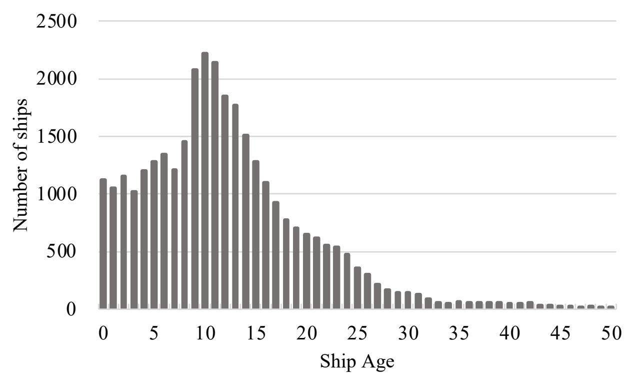

Figure 2: Ship age distribution of the initial fleet

This case study considered the following five types of ships, heavy fuel oil ship (HFO), dual fuel ship of HFO and LNG (DF(HFO, LNG)), dual fuel ship of HFO and Ammonia (DF(HFO, NH_3)), dual fuel ships of HFO and Methanol(DF(HFO, Methanol), and H_2 fueled ship. DF(HFO, LNG) has already been widely used and the DF(HFO, Methanol)'s technology is considered sufficiently mature. However, DF(HFO, NH3) and H_2-fueled ships are at the R&D stage and are unlikely to be implemented soon. In this case study, it is assumed that DF(HFO, NH3) and H_2-fueled ships can be introduced in 2028. This assumption is based on Japan the Ministry of Land, Infrastructure, Transport and Tourism of Japan's development roadmap (MLIT, 2021), which shows that the implementation of the alternative fuel technology will begin to be introduced in 2028 at the earliest. In the proposed simulation method, the introduction rate of each ship type can be inputted as a scenario. For the near future, it is possible to estimate the percentage of ships introduced from the information in the order book. Based on the Clarkson Shipping Intelligence Network (SIN) data (Clarkson, 2023), a scenario was developed for the percentage of ships that will be deployed from 2022 to 2026. The SIN provides data on deliveries and orderbooks. By aggregating data on containers, bulkcarrier, tankers, PCC, and general cargo, the percentage of each ship type was calculated. The results are shown in Figure 3. The proportion of both LNG- and methanol-fueled ships has increased.

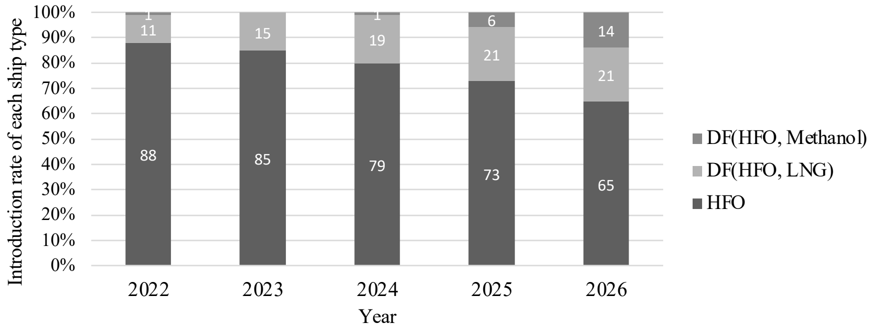

Figure 3: Percentage of ships introduced from 2022 to 2026

Figure 4 shows the setting of the ships, which was assumed based on the IHS Seaweb's ship cost data and references from the IMO 4th GHG Study's MACC calculation. The values at the top of the bars in the figure indicate the ratio of the costs when based on HFO-fueled ships. DF(HFO, Methanol) ship was set as the cheapest ship and the H_2-fueled ship was set as approximately 40% more expensive than the HFO ship.

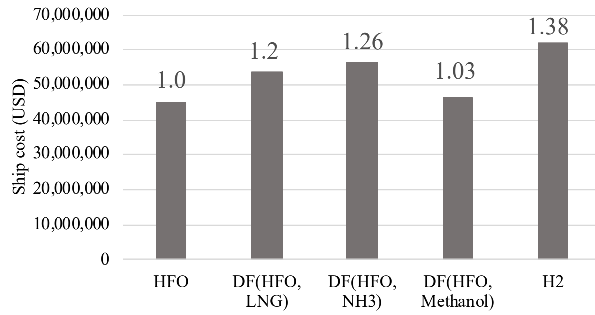

Figure 4: Setting of ship costs in case study

Figure 5 presents the survivor curve profile for this case study. Historical data on scrapped ships from the IHS Sea-web database were compiled to create a relationship between age and scrapping, with the maximum age set at 50 years old.

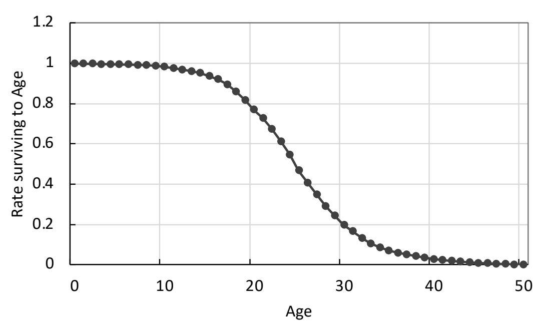

Figure 5: Survivor curve profiles for the case study

Fuel scenarios

To conduct a simulation based on the proposed method, it was necessary to define the fuel WtW emission factors, future costs, and availability. Although it is difficult to predict future trends in fuels owing to significant future uncertainties, the simulation in this study was based on the results of the JTTRI internal study in which scenarios were developed based on the literature and available data.

Table 1 presents the assumed WtW GHG emission intensity (gCO2eq/MJ). The fuels' tank-to-wake (TtW) GHG emission intensity does not vary with time because of its chemical properties, but the WtT GHG emissions can change based on trends in the decarbonization of the energy production industry, such as renewable energy penetration.

Therefore, the case study assumes that the WtW emission intensity changes with time. The IMO's newest GHG reduction strategy describes decarbonization around 2050, which is based on the IEA NZE scenario and the WtW GHG intensity of biofuels and e-fuels (green) decreases to 0. Table 2 presents the assumed fuel costs (USD/GJ).

Table 1: WtW GHG intensity (gCO_2eq/MJ) setting of 2030, 2040, and 2050.

Fuel label	2030	2040	2050
LSFO	90.0	90.0	90.0
LNG	71.7	65.1	58.3
BioHFO	4.9	2.4	0
BioMethane	7.5	3.1	0
BioMethanol	6.9	2.9	0
eMethanol(Brown)	91.7	90.8	90.7
eAmmonia(Brown)	114.2	112.3	111.2
H_2(Brown)	93.1	91.1	90.2
eMethane(Blue)	28.4	13.5	5.4
eMethanol(Blue)	31.4	14.7	5.9
eAmmonia(Blue)	15.6	7.3	2.9
H_2(Blue)	13.3	6.1	2.4
eMethane(Green)	4.6	0	0
eMethanol(Green)	5.8	0	0
H_2(Green)	5.3	0	0

Table 2: Fuel cost (USD/GJ) setting for 2030, 2040, and 2050.

Fuel label	2030	2040	2050
LSFO	6.8	5.9	4.9
LNG	14	13.8	13.7
BioHFO	63.2	60.2	57.6
BioMethane	32.3	29.2	26.2
BioMethanol	24.6	21.6	18.7
eMethanol(Brown)	13.8	13.2	12.6
eAmmonia(Brown)	19.2	18.7	18.2
H_2(Brown)	40.2	37.7	35.2
eMethane(Blue)	39.3	38.4	37.5
eMethanol(Blue)	35.3	34.1	32.9
eAmmonia(Blue)	23.8	23.3	22.7
H_2(Blue)	44.2	41.7	39.1
eMethane(Green)	40.7	38.2	35.6
eMethanol(Green)	40.8	37.6	34.4
H_2(Green)	35.9	33.3	30.8

As for the fuels' availability, we assumed two kinds of scenarios, "High Bio" and "Low Bio". Biofuels are essential alternative fuels for the shipping decarbonization. Fuels are also promising for the aviation and land transportation industries. In the high-biofuel scenario, assuming that other industries would implement more decarbonization through electrification, the availability of biofuels was set. However, it was assumed that biofuels would be used more in other industries and that their availability in the maritime industry would be significantly reduced. Figure 6 shows the fuel availability for each scenario.

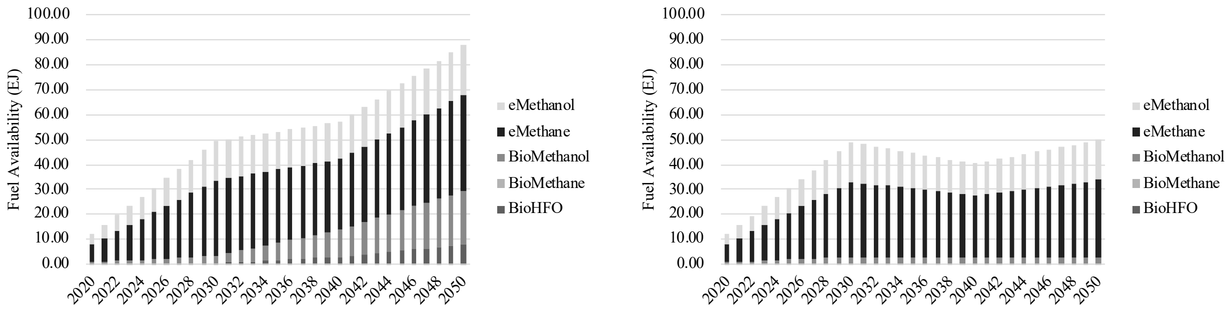

Figure 6: Fuel availability scenarios (Left: High Bio, right: Low Bio)

Other Scenarios

For transportation demand, two scenarios were chosen from the 4th IMO GHG Study's assumptions; RCP2.6 OECD and RCP2.6 SSP2. They are called "Low" and "High" in this paper. Various scenarios were considered in the IMO study. From these scenarios, we selected the maximum and minimum scenarios to comply with the 2°C target of the Paris Agreement. The indicative checkpoints in the 2023 IMO target are defined for the total GHG emissions from international shipping; thus, the GFI pathways for implementing them have different individual values for each transportation demand. In this case study, the indicative checkpoints were defined as a 20%, 70%, and 100% reduction in 2030, 2040, and 2050, respectively, in WtW emissions compared to that in 2008. Table 3 summarizes the transportation demands and GFI pathways used in the case study. Notably, the GFS regulation is under discussion at the IMO, and the GFI pathways described in the table are based on the assumption that the IMO indicative checkpoints are achieved by GFS regulation alone.

Table 3: Transportation demand and GFI pathways of 2030, 2040, and 2050

Transportation demand label		2030	2040	2050
Low	Demand (billion ton mile)	6.7×10^4	7.6×10^4	8.2×10^4
	GFI (LSFO = 100)	95.2	34.7	0
High	Demand (ton mile)	8.2×10^4	1.0×10^5	1.2×10^5
	GFI (LSFO = 100)	78	26	0

Results

Case 1: Comparison of cases with/without the flexibility mechanism

In Case 1, simulations of cases with and without a flexibility mechanism were conducted, and the impact of the flexibility mechanism was evaluated by comparing the results. The fuel availability scenario was set as High Bio, and the RCP2.6 OECD (scenario: low) was selected for transportation demand. For the notation, the case without the flexibility mechanism is Case 1-1, and the case with the flexibility mechanism is Case 1-2. Figure 7 presents the result of Case 1-1, which shows fuel consumption and WtW emissions from the overall fleet until 2050. The WtW emissions are normalized by the 2008's emission. The bar chart shows each fuel consumption (EJ=10^{12}MJ). In this case study, 15 fuels were assumed to be potential candidates for alternative fuels; however, by selection based on the cost, fuel decomposition can be expressed by the seven fuels in the figure. HFO-fueled ships are adapted to the GFS regulations by using BioHFO as a drop-in fuel. The DF(HFO, LNG) utilizes a combination of LNG and eMethane(Green) as the most cost-effective option. The DF(HFO, Methanol) primarily consumes BioMethanol. The DF(HFO, NH_3) was operated mostly with a mixture of LSFO and eAmmonia(Blue) and eAmmonia(Green) was used only in the last two years of the simulation. Especially for HFO-fueled ships, biofuels must be utilized to adapt the regulation in the case without the flexibility mechanism. Based on the simulation result, 0.30 EJ of BioHFO will be required as of 2030. Moreover, owing to the insufficient availability of BioHFO, the GFI pathway cannot be implemented from 2033 to 2036, as indicated by the shaded areas in the Figure 7.

This implies that more BioHFO is required for HFO ships to comply with the GFI pathway. Although the indicative checkpoints for 2030, 2040, and 2050 are achieved, it is a possible risk factor that parts of the pathway cannot be achieved.

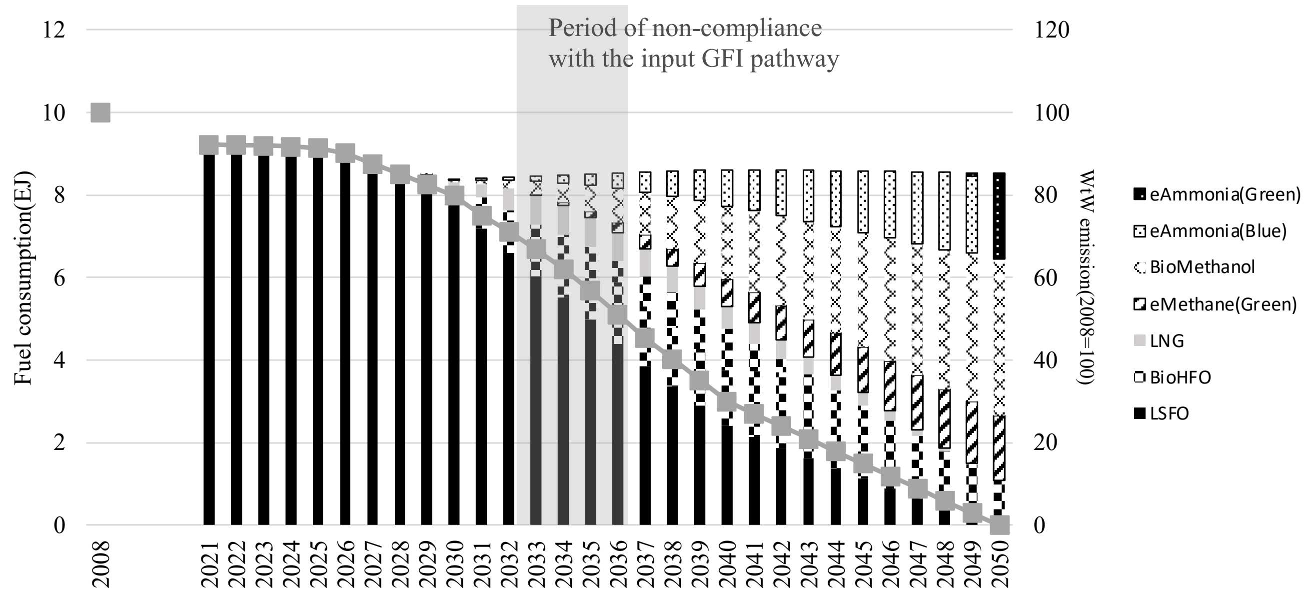

Figure 7: Fuel consumption and WtW emissions (Case 1-1, case without flexibility mechanism)

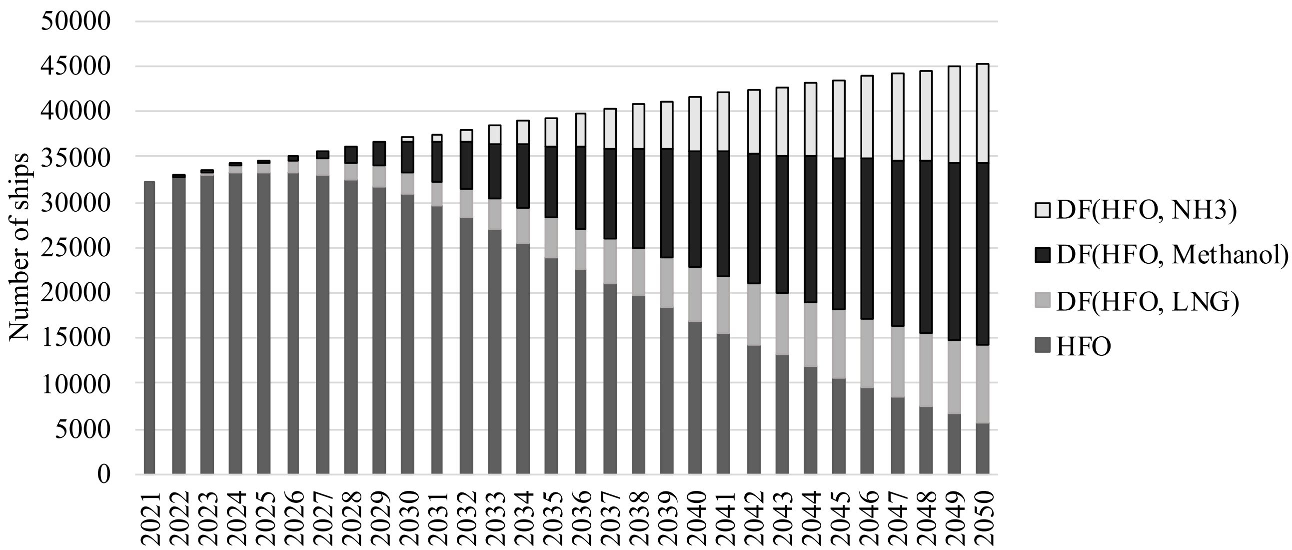

Figure 8: Fuel decomposition (Case 1-1, case without flexibility mechanism)

Figure 8 shows the results of the fleet decomposition from 2021 to 2050. The vertical axis represents the number of ships operating annually. From 2026 to 2028, the introduction of DF(HFO, NH_3), DF(HFO, LNG), and DF(HFO, Methanol) penetrated the fleet to adapt to the GFS regulation. Finally, DF(HFO, NH3), DF(HFO, Methanol), and DF(HFO, LNG) were introduced in that order. This is due to the total cost of CAPEX and fuel cost, and the high availability of inexpensive BioMethanol.

The results of Case 1-2 are shown in Figures 9 and 10, respectively. They are the results of the flexibility mechanism. As shown in Figure 10, there is not much difference in the fleet decomposition to comply with the GFS regulation, except that the introduction period of HFO ships is extended by two years. However, Figure 9 indicates that the fuel consumption composition is significantly different from that in Case 1-1. While in Case 1-1, HFO-fueled ships utilized BioHFO to comply with the regulation, in Case 1-2 with the flexibility mechanism, HFO-fueled ships did not utilize biofuels, and ships fueled by others compensated to achieve the GFI pathway. In this scenario, although BioHFO is more expensive and not as abundant in supply as other green fuels, the results indicate that it is possible to promote emission reduction by ships fueled by other fuels and implement the GFI pathway for the entire period.

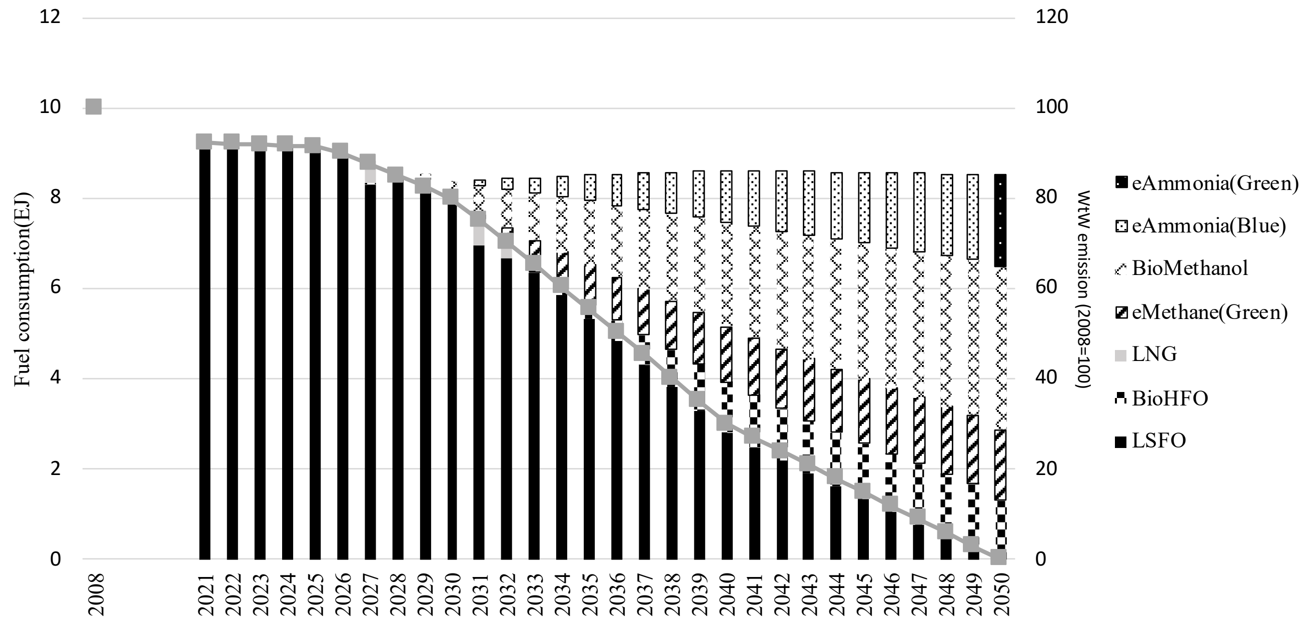

Figure 9: Fuel consumption and WtW emissions (Case 1-2, case with flexibility mechanism)

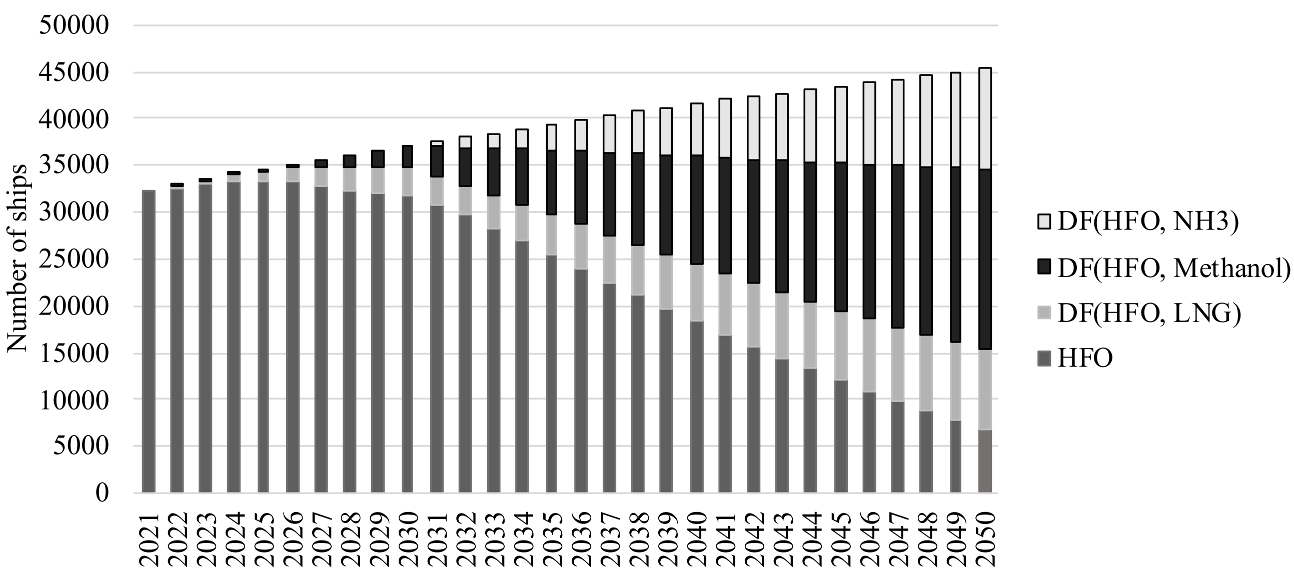

Figure 10: Fleet decomposition (Case 1-2, case with flexibility mechanism)

A cost comparison between Cases 1-1 and 1-2 is shown in Figure 11 to illustrate the effect of the flexibility mechanism in more detail. Figure 11 indicates that the fuel cost is affected by the flexibility mechanism, especially for 2040. When the flexibility mechanism is applied, the fleet can select a more cost-effective fuel mix according to fuel costs and availability beyond the constraints of the fuel type of individual ships, thereby, reducing transportation costs in the overall shipping market when complying with the regulations.

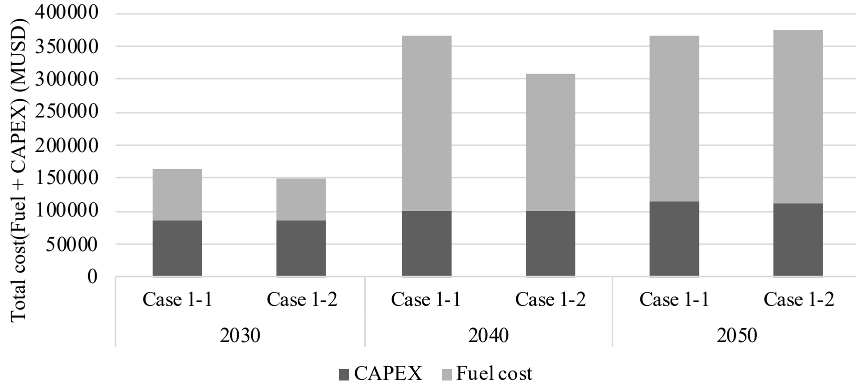

Figure 11: Comparison of costs between Cases 1-1 and 1-2 in 2030, 2040 and 2050

Case 2: Exploration of feasible GFI pathway

Shipbuilding can take years; thus, the replacement cannot proceed rapidly, and deployment of the fuel supply chain is an unaddressed issue. Therefore, setting the GFI pathway incorrectly would render the GFS regulation unfeasible. In this case study, assuming that a severe scenario is applied (transportation demand is "High" and "Low Bio"), a GFI pathway that is feasible and contributes most to GHG emission reduction should be explored.

The exploration process is as follows: First, in addition to the GFI pathway presented in Table 3, four pathways with less restrictive GFI values were prepared. The FuelEU Maritime reduction target was adopted as the most feasible pathway. Each of these pathways was input into the simulation to examine their feasibility for 2030 and 2040. A feasible line that contributes as much as possible to GHG emission reductions up to 2040 is defined as a solution. The final GFI target for 2050 is the input in increments of 5 from 0 to 20 to find a feasible point that contributes to GHG emission reduction as much as possible. The input GFI pathway candidates are listed in Table 4.

Table 4: Input GFI pathways of 2030, 2040, and 2050 for Case 2.

Year	2030	2040	2050
GFI candidates (LSFO=100)	94	69	20
	90	58.25	15
	86	47.5	10
	82	36.25	5
	78	26	0

The discovered solution pathway is presented in Figure 12. For reference, the GFI pathways that comply with the IMO GHG reduction strategy and FuelEU Maritime are also illustrated. As a result of the exploration, the pathway that complies with the IMO's reduction indicative checkpoint until 2030, passes between FuelEU Maritime and the IMO target, and finally reduces the GFI by 80% compared to LSFO was found. This result means that if the transportation demand becomes high, and biofuel availability is low, it is difficult to achieve the IMO's indicative checkpoint using only the GFS regulation. When the proposed pathway is applied, 26% more reduction in 2040 and 25% more reduction in 2050 by other measures such as the MBM, is required to achieve the IMO's indicative checkpoints.

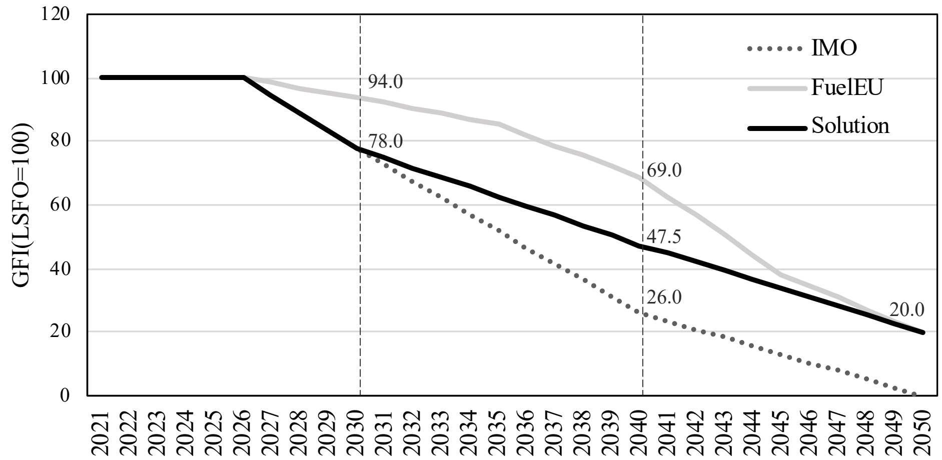

Figure 12: Exploration result of the feasible GFI pathway under a severe scenario

DISCUSSION

Case 1 compares the GFS regulation with and without the flexibility mechanism via the simulation. In addition to introducing alternative fuel ships, it is important to consider how existing ships comply with the regulations. The results of the comparison show that the presence of the flexibility mechanism can eliminate the period of non-compliance with the regulations owing to the availability of BioHFO. Moreover, the cost comparison shows that the flexibility mechanism can reduce the costs, especially fuel costs, required to adapt to the regulation. This results from the flexibility mechanism, allowing the fleet to utilize not only BioHFO but also more diverse and cost-effective fuels to adapt existing ships to the regulations. While these results are limited to the specific scenario assumed in the case study, the general insight from the results is that the flexibility mechanism can diversify options to comply with the regulation, especially for the existing ships, and thus promote more efficient decarbonization across the fleet.

However, the introduction of the flexibility mechanism has disadvantages, as it requires a more complex implementation, such as an emission trading mechanism. Decisions on whether to introduce the mechanism should be based on a consideration of these advantages and disadvantages. The proposed method allows for a quantitative evaluation of its advantages and is useful for supporting the decision-making processes.

In Case 2, a feasible GFI pathway that contributes to decarbonization as much as possible was explored with a higher transportation demand and lower biofuel supply than in Case 1. The results show that the proposed method can support the design of the GFS, as it can output a feasible GFI pathway and the amount of the GHG reduction required to achieve the IMO's indicative checkpoints by other measures such as MBM.

The case study in this paper is based on a specific scenario out of many future scenarios, and a more detailed consideration of future uncertainties is required in the actual regulation design. Specifically, the transport demand, fuel costs, and availability scenarios are highly uncertain, and the results of the case studies can change if the scenario is different.

Lagouvardou, et al. (2020) pointed out the uncertainty of the market conditions, and it is estimated that there are deep uncertainties in the fuel scenario, the cost of alternative fuel ships, and transportation demand. The results of the case study should be read with this limitation, and it is one of the future works to consider the impact of such deep future uncertainty. Hiekata et al. (2015) generated large scenarios based on a binomial lattice model and utilized the Monte Carlo simulation method to evaluate the scenarios. Irena et al. (2021) considered the uncertainties by sensitivity analysis when calculating the MACC of CO_2 mitigation measures for the decarbonization of shipping. The approach used in these studies will be useful for future research.

In addition, improving the model for the share of fuel ship types in the simulation is a topic for future research. It is difficult to model this behavior because there has never been a situation in international shipping where multiple fuels have been candidates for use, and they constitute market share. However, at present, various fuels are being handled in development projects for alternative fuel ships, and because best practices have not yet been established, they are considered to form a market share. In automotive studies, discrete choice models such as logit models are utilized to model users' behavior in choosing vehicle and fuel types based on preference data and interviews with users (Hess et al., 2012;

Khan et al., 2020; Yoo et al., 2021). Incorporating the current shipping company's preferences into the model through surveys and the modeling is a possible direction for the model improvement.

CONCLUSIONS

This study quantitatively examined how the GFS regulation affects international shipping through simulations that project future fleet transformation, fuel consumption, and WtW GHG emissions based on an inputted GFI pathway and scenario of transportation demand, fuel availability and costs, and technology availability. The method consists of three models, shipbuilding and scrapping, fuel and ship selection, and calculation of emissions and cost, and enabling us to study the regulation quantitatively from the perspective of feasibility and cost. The fuel and ship section model can express the difference between the cases with and without the flexibility mechanism, and in the simulator, it is possible to quantify the differences. Two case studies were conducted using simulation. First, we compared the simulation results with and without the flexibility mechanism. It was shown that the introduction of the flexibility mechanism allows more options for achieving the regulation as of 2030, especially for existing vessels, and that there are benefits for the cost of overall international shipping. In the second case, GFI pathways that are feasible and contribute to GHG reduction as much as possible were explored by using the simulation. As shown in the results of Case 2, the simulator can search the pathways by inputting transportation demand, fuel availability scenario, and candidates of GFI pathways, demonstrating that the proposed method is useful in designing the feasible GFS regulation according to the transportation demand, and fuel availability.

CONTRIBUTION STATEMENT

Shinnosuke Wanaka: conceptualization; data curation; methodology; software; visualization; writing – original draft. **Kazuo Hiekata:** conceptualization; supervision; writing – review and editing. **Tomohito Takeuchi**: conceptualization; project administration; writing – review and editing. **Masanobu Taniguchi**: conceptualization; investigation; writing – review and editing.

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