BIOFUEL AS MARINE FUEL

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Contents

01

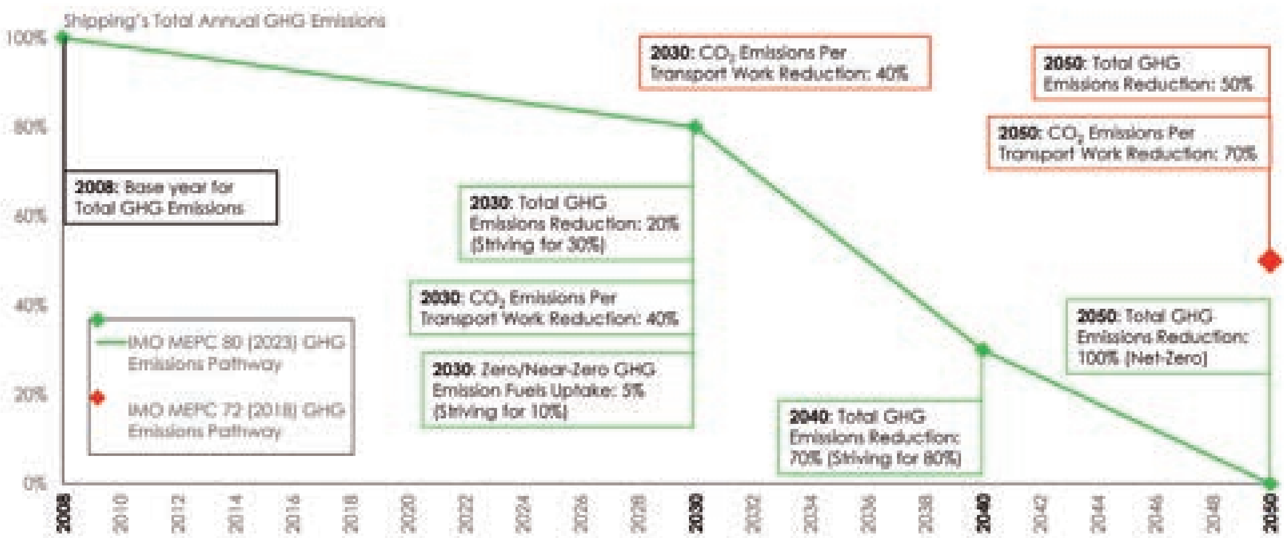
Introduction

1.1 General information

Biofuels are renewable fuels produced from biomass, which refers to organic materials such as plant matter, animal waste, agricultural crops, forestry residues, and organic waste through various conversion process. It possesses chemical characteristics similar to those of petroleum products, and is categorized as an alternative fuel. This categorization is based on compatibility with existing internal combustion engines and infrastructure without necessitating structural alterations. Biofuels are characterized by lower carbon content than traditional fossil fuels. They are derived from biomass, which captures carbon dioxide from the atmosphere. Consequently, they are classified as carbon-neutral fuels, and their applications are expanding across various industries.

At the 80th meeting of the Marine Environment Protection Committee (MEPC) of the International Maritime Organization (IMO), a greenhouse gas strategy was established. This strategy includes setting a goal of net zero by or around 2050. Consequently, the shipping sector must reduce greenhouse gas (GHG) emissions through various technical and operational measures.[1] Although most ship orders still favor traditional fossil fuels, there is growing consideration for the use of alternative fuels with high greenhouse gas reduction potential to meet emission reduction goals. Consequently, the proportion of ships utilizing these fuels has increased. As most ships rely on internal combustion engines for propulsion and power, interest in biofuels is increasing. Biofuels are highly effective and immediate alternatives to other fuels, offering a swift response to regulatory requirements.

Various sea trials have been conducted for the application of biofuels. These involve the use of biofuels mixed with existing fossil fuels or the complete replacement of conventional fuels. Biofuels



|Figure 1-1| The greenhouse gas reduction strategy confirmed at the 80th IMO's MEPC session[1]

have the characteristic of being 'drop-in' fuels, which means that they can be used immediately without major modifications or changes to internal combustion engines used for marine propulsion or power generation. If a sufficient and consistent supply of biofuels is available, they can be utilized not only as the primary fuel but also as a pilot fuel in dual-fuel engines. This enables the achievement of net zero emissions in ships, leading many shipping companies to consider the application of biofuels.

Engine manufacturers are also providing guidelines[2,3] for the proper use of biofuels and are releasing engines equipped with technology that guarantees the inherent maximum output of the engine, even when using biofuels with lower calorific values (LHV).[4]

Shippers actively participate in biofuel use. For example, Amazon co-founded the 'Climate Pledge' program with Global Optimism, with over 400 companies from 38 countries worldwide participating, aiming for zero carbon emissions by 2040. As part of this program, Amazon plans to use biofuels to transport 20,000 containers (40-foot) in contract with A.P. Moller, expecting to reduce approximately 44,600 tons of CO_{2e} emissions.[5] In another instance, Volvo Cars anticipated saving approximately 55,000 tons of carbon dioxide annually by using biofuels based on waste cooking oil for the maritime transportation of their auto parts.[6]

Biofuels can be used not only in large ocean-going vessels, but also in coastal fishing boats using high-speed diesel engines. Countries where fishing is a major industry on older and less efficient vessels that employ fuel-intensive fishing methods. Reportedly, mixing 16% waste cooking oil-based biodiesel in fishing boats can reduce CO_{2e} emissions by up to 11% from an overall life-cycle perspective (Well to Wake). Furthermore, increasing the biodiesel blend to 24% and improving fishing methods could reduce CO_{2e} emissions by up to 43%.[7]

Quality standards for biofuels remain underdeveloped, and there are few examples of their long-term use in ships. Therefore, shipping companies considering the application of biofuels need to thoroughly assess their safety and environmental impacts beforehand. For instance, while biofuels have the advantage of relatively easier storage and handling compared to other alternative fuels, it is important to note that storage conditions and duration can vary depending on the type of biofuel and feedstocks, necessitating careful consideration.

For the continuous use of biofuels as marine fuels, considerations such as sustainability, economic viability, and supply stability must be addressed. Compliance with the regulations on air pollutants and GHGs is crucial.

This technical document provides information on the common types and characteristics of biofuels that can be used on ships along with quality guidelines. Potential operational issues and their solutions are also discussed. Furthermore, the document explains the current situation regarding GHG regulations and presents case studies on how the use of biofuels can aid regulatory compliance, thereby offering insights into the feasibility of biofuels as marine fuels.

1.2 Status and prospects of alternative marine fuels

In response to global and regional GHG regulations, the use of various alternative fuels is anticipated in the maritime sector to reduce GHGs and achieve net zero emissions.

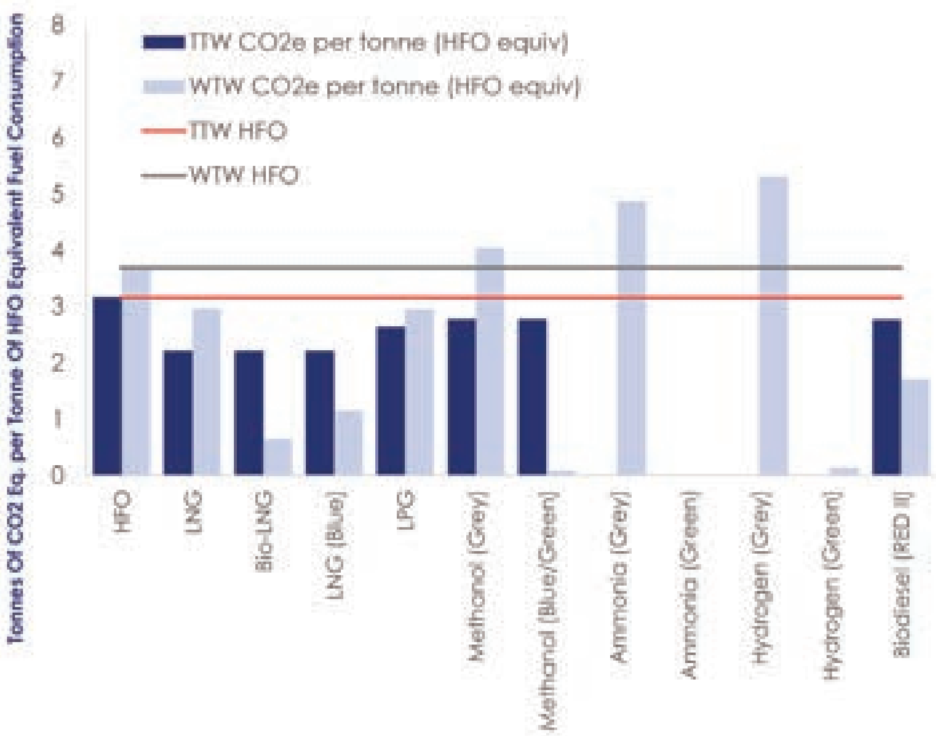
Liquified natural gas (LNG), which is recognized for its low carbon content, is the leading low-carbon fuel option. It gained prominence as a response to the sulfur oxide regulation (0.5% S) that began in 2020. With the strengthening of GHG regulations, LNG is increasingly being used in various types of ships. LNG demonstrated a 24% CO_2 reduction from the tank-to-wake (TtW) perspective. To compensate for its relatively lower CO_2 reduction effect compared to zero-carbon fuels, combinations of technologies, such as Onboard Carbon Capture and Storage (OCCS) and dual-fuel engines that can burn a mix of zero-carbon fuels, are being developed. Furthermore, sustained use of LNG is anticipated by blending or replacing it with biomass-based bio-LNG and renewable-energy-based E-LNG. Moreover, various technologies are being developed to reduce the methane slip, which is a key issue in LNG propulsion ships. These include enhancements in combustion, combustion chamber optimization, and exhaust gas recirculation devices, as well as post-treatment technologies such as methane oxidation catalysts. These advancements aim to reduce emissions of unburned methane, which is the primary component of LNG. Some of these technologies are already being implemented.

Currently, LPG fuel is mainly used in LPG carriers, with traditional fossil-fuel-using LPG carriers being converted to LPG-fueled ships in some cases. The fossil fuel-based LPG currently in use has a relatively low CO_2 reduction effect of approximately 13-18%, but the potential use of bio-LPG, which has a lower carbon intensity, is gaining attention. Bio-LPG is a byproduct of Hydrotreated Vegetable Oil (HVO) and Sustainable Aviation Fuel (SAF). As the production of these fuels increases, bio-LPG production is also expected to increase.[8] In the event of implementing regulations from an overall life-cycle perspective, a mix or replacement of fossil fuel-based LPG with bio-LPG could offer a way to comply with stricter regulations.

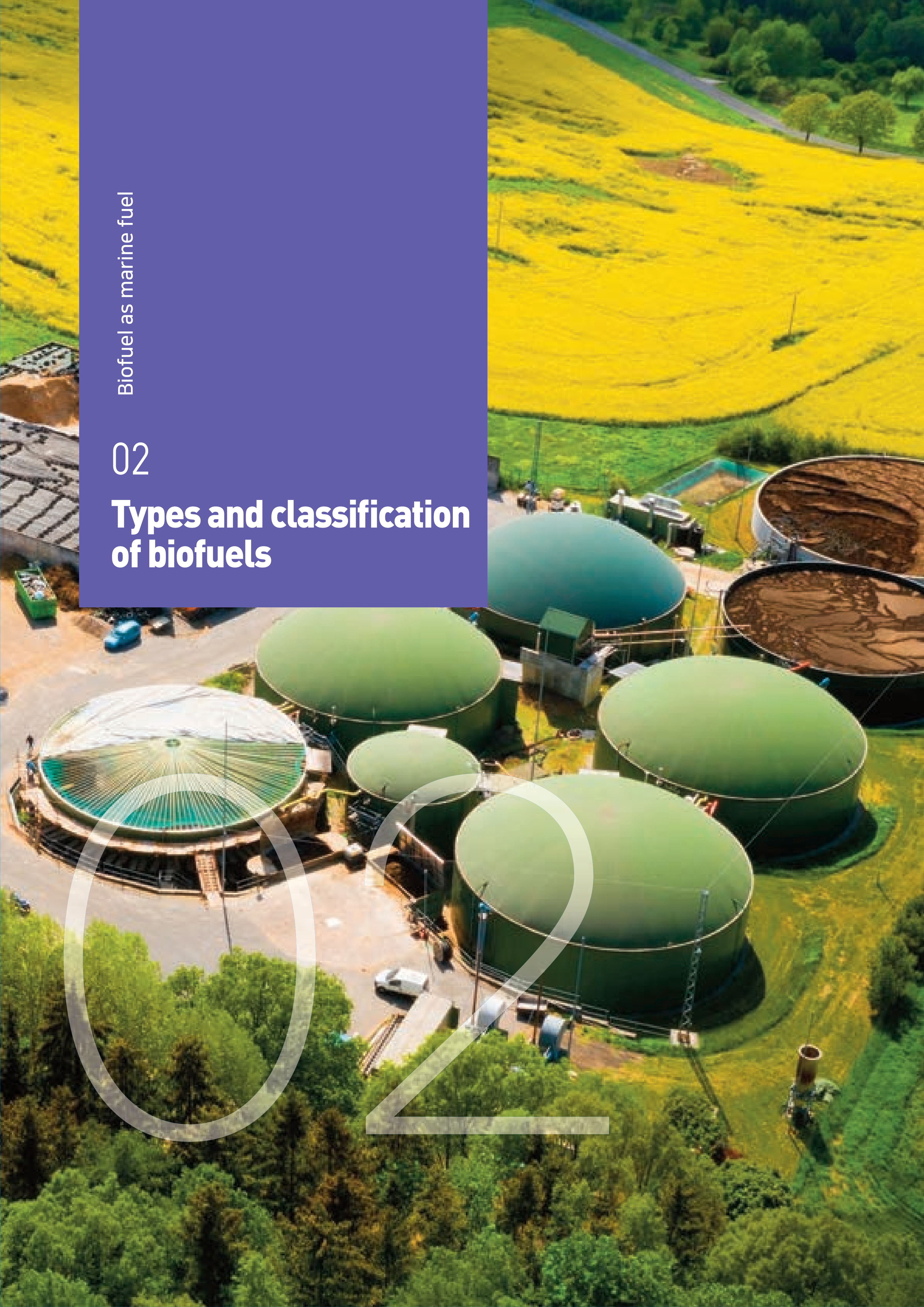
Methanol fuel, recently ordered for use in various ship types, contains ~37% carbon in its molecular structure. Thus, under the current regulations (from a tank-to-wake perspective), the GHG reduction rate is lower than that of low-carbon fuels such as LNG or zero-carbon alternatives such as ammonia and hydrogen. However, methanol fuel has attracted attention owing to its relative ease of storage and handling and the potential use of non-fossil methanol derived from biomass or green hydrogen. The use of green methanol (Bio-methanol, E-methanol) can achieve over 90% GHG reduction compared to fossil fuels from a well-to-wake perspective. However, considering the uncertainties in supply and potentially high fuel costs, securing green methanol suppliers or establishing partnerships is crucial when considering the procurement of methanol-fueled ships.

Ammonia, a prominent zero-carbon fuel, results in no CO_2 emissions from a TtW perspective when used solely as a fuel. However, as depicted in Figure 1-2, gray ammonia, which is based on fossil resources, has higher GHG emissions compared to Heavy Fuel Oil (HFO) when assessed from a well-to-wake (WtW) perspective. Therefore, to meet the increasingly stringent GHG regulations, the use of clean ammonia (blue ammonia, E-ammonia), rather than fossil-based ammonia, is necessary. Additionally, precautions regarding the toxicity and corrosiveness of ammonia fuels are required. Engines capable of using ammonia fuel are currently under development, and they are expected to be installed in recently ordered Very Large Ammonia Carriers (VLACs).

In summary, various alternative fuels are expected to play crucial roles in reducing air pollutants and GHGs. Furthermore, the existing alternative fuels, when mixed or replaced with biomass-based or green hydrogen-based 'drop-in fuels,' are anticipated to respond to the tightening GHG regulations. However, as all alternative fuels have their own set of challenges, including regulations, fuel price, and bunkering infrastructure uncertainties, it is expected that these fuels will not compete but rather complement each other in reconfiguring future shipping fleets. This will likely influence the proportion of alternative fuel-powered ships in fleets, depending on the availability, pricing of fuels, and regulatory and policy directions, such as carbon taxes. In this context, biofuels, which can be readily applied to existing ships, are also expected to play a significant role in the maritime industry's journey towards net-zero.



|Figure 1-2| Comparison of emissions by alternative fuels according to greenhouse gas calculation methods[1]



02

Types and classification of biofuels

2.1 Types of biofuels

Biofuels can be produced from a wide range of raw materials, including vegetable oils, animal fats, and waste resources, such as wood waste and used cooking oil, using various manufacturing methods. Bio-methanol and bio-LNG can also be classified as biofuels; however, this document primarily describes biofuels that can directly replace traditional fuel oils (such as HFO and MDO) used for propulsion and power generation in conventional diesel engines. Furthermore, in this chapter, we focus intensively on fatty acid methyl ester (FAME) and HVO fuels, which have a higher degree of technological maturity, as shown in Table 2-1. Biofuels with relatively low technological maturity (below level 9) are briefly reviewed.

|Table 2-1| Comparison of technological maturity by alternative fuel[9]

Fossil fuel replaced	Type of biofuel	Process pathway and Technology Readiness Level(TRL)				Feedstock
		Process step 1	TRL	Process step 2	TRL	
Residuals and distillate (e.g., HFO, VLSFO, MGO)	Fatty acid methyl esters (FAME)	Transesterification	9	-	-	Waste fats, oils, greases (FOG; Fat, Oil, Grease)
	Hydrotreated vegetable oils(HVO)	Hydroprocessing	9	-	-	
Liquified natural gas (LNG)	Synthetic natural gas (SNG)	Anaerobic digestion	9	Methane synthesis from carbon dioxide(CO_2)	9	Agricultural residue, sewage sludge, food waste
Fossil-based methanol	Bio-methanol	Anaerobic digestion to methane	9	Synthesis	9	Agricultural residue, sewage sludge, food waste
		Gasification of biomass	7			Lignocellulosic biomass
Residuals (e.g., HFO, VLSFO)	Fast pyrolysis (FP) bio-oil	Pyrolysis	8-9	Upgrade	6	Lignocellulosic biomass, forestry/ agricultural residue
	Hydrothermal liquefaction (HTL) bio-oil	Hydrothermal liquefaction	6	Upgrade		Lignocellulosic biomass, forestry/ agricultural residue, wet waste

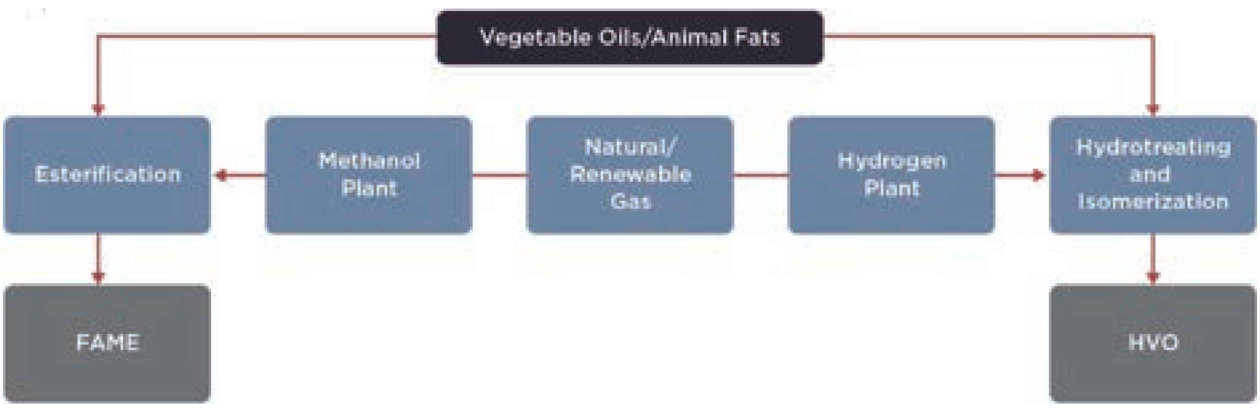
2.1.1 FAMEs

FAMEs are produced by reacting bio-oil (triglycerides) with methanol or ethanol in the presence of a catalyst via a transesterification process. Triglycerides, found in vegetable oils or animal fats, consist of three fatty acids and one glycerol molecule linked by ester bonds. During transesterification in the presence of a strong alkaline catalyst such as sodium or potassium hydroxide, glycerol is separated and remains as a by-product, whereas methanol combines with fatty acids to form FAME. Commonly considered as biodiesel, FAMEs are produced using various raw materials, such as rapeseed oil, palm oil, corn, coconut, animal fats, and waste cooking oils.

2.1.2 HVO

HVO can be produced from the same raw materials as FAME and can utilize lignocellulosic biomass. It is a fuel manufactured through hydrogenation and cracking, forming paraffinic hydrocarbons, similar to conventional fossil fuel refining processes. At high temperatures and pressures, in the presence of nickel- or cobalt-based catalysts, the double bonds of fatty acid molecules and carbon atoms are converted into single bonds through hydrogen addition, and oxygen-containing impurities are removed. After this hydrogenation process, the fuel is refined to produce HVO, which has properties similar to those of marine gas oil (MGO) and other distillate fuels and is characterized by a low sulfur content and viscosity. When using HVO alone, it is necessary to evaluate its lubricating properties.

Figure 2-1 illustrates the production processes of FAME and HVO, representative biofuels, while Table 2-2 compares the properties of current fossil fuels and these biofuels, as detailed in Table 2-1.



|Figure 2-1| FAME and HVO manufacturing process[10]

|Table 2-2| Comparison of properties of fossil fuels and biofuels[2]

Contents	Properties with fuels					
	FAME	HVO	Blends	ULSFO	VLSFO	HSFO
Nitrogen [%]	~0.1	~0	~0.1-0.4	~0.1	~0.4	~0.4
Oxygen [%]	~10	~0	~0-10	~0	~0	~0
Sulfur [%]	~0	~0	Low	≤0.1	≤0.5	>0.5(ave.2.9)
LCV [MJ/kg]	37	43	37-43	42-43	39-42	39-41
Kin. Visc. [mm^2 /s]	3-5 at 40℃	2-3 at 40℃	Low*	2-11 at 40℃	2-500 at 50℃	200-700 at 50℃
Pour point [℃]	<-6 to +6	Low	*	ISO 8217	ISO 8217	ISO 8217
Stability	Low-high**	Very high	Medium-high	Very high	High	High
Lubricity	Analysis***	Analysis***	Analysis***	ISO 8217	ISO 8217	ISO 8217
Standard	EN 14214, ASTM D6751	EN 15940: 2016+A1:2018+AC, ISO 8217 DMA grade	No standard**** ISO 8217: 2017: up to 7% FAME in DM	ISO 8217	ISO 8217	ISO 8217

* Depending on the biofuel blend ratio and properties of the bio-part and fossil fuels.

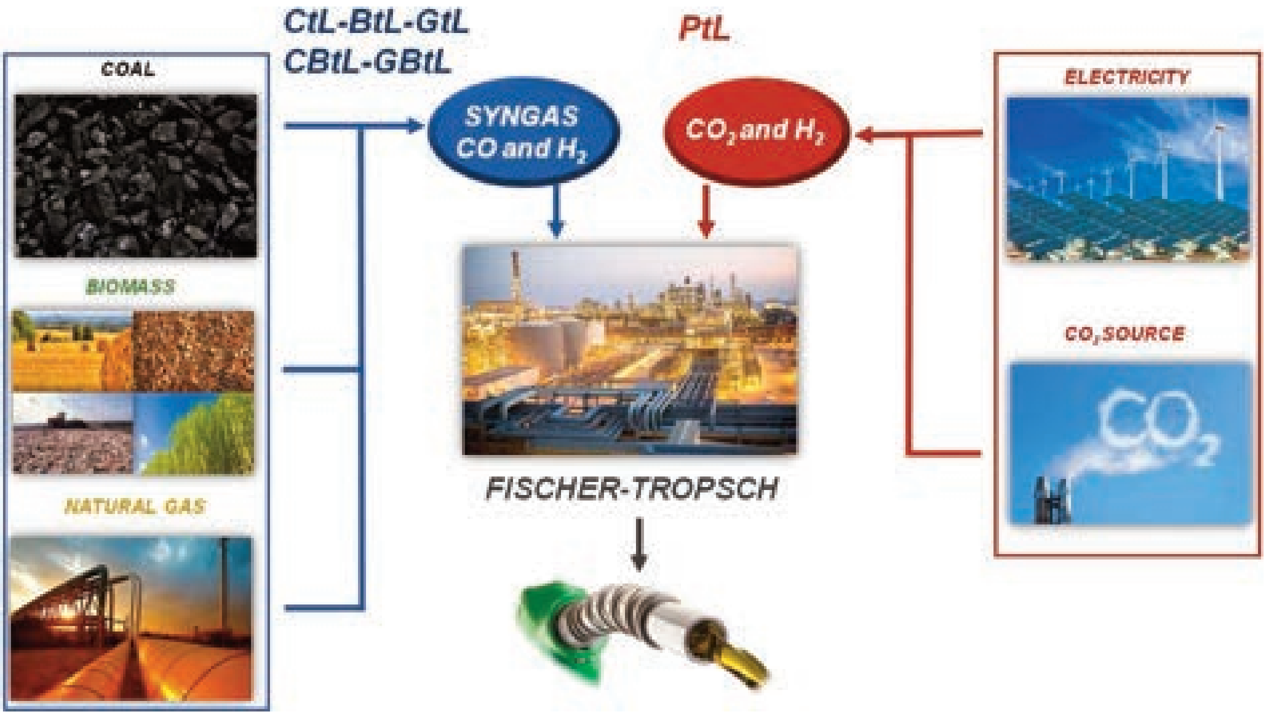
** Depending on FAME feedstock

*** Most relevant for fuels with lower than 0.05% sulfur (500 ppm S)

**** Standards are updated from time to time. Please refer to the latest version of this manuscript.

2.1.3 Fischer-Tropsch (FT) diesel

FT diesel, as depicted in Figure 2-2, is produced through gasification and Fischer-Tropsch synthesis processes using coal, natural gas, and biomass as the primary feedstocks. Fuel manufactured via the FT process using a variety of biomasses, including agricultural residues and woody materials, is referred to as Biomass to Liquid (BTL). The BTL process comprises four stages: 1) transportation, storage, handling, and pretreatment of biomass; 2) gasification, followed by cleaning and conditioning of the synthesis gas; 3) FT synthesis; and 4) upgrading. Through this sequence of steps, the BTL fuel is produced. Almost any type of biomass can serve as feedstock for BTL, which combines the economic benefits of coal-based Coal to Liquid (CTL) fuel production with low capital costs and hydrogen addition savings from natural gas-based Gas to Liquid (GTL) fuels. Consequently, it can also be manufactured as coal- and biomass-to-liquid (CBTL) or gas- and biomass-to-liquid (GBTL) fuels, which are produced using more than one type of feedstock.



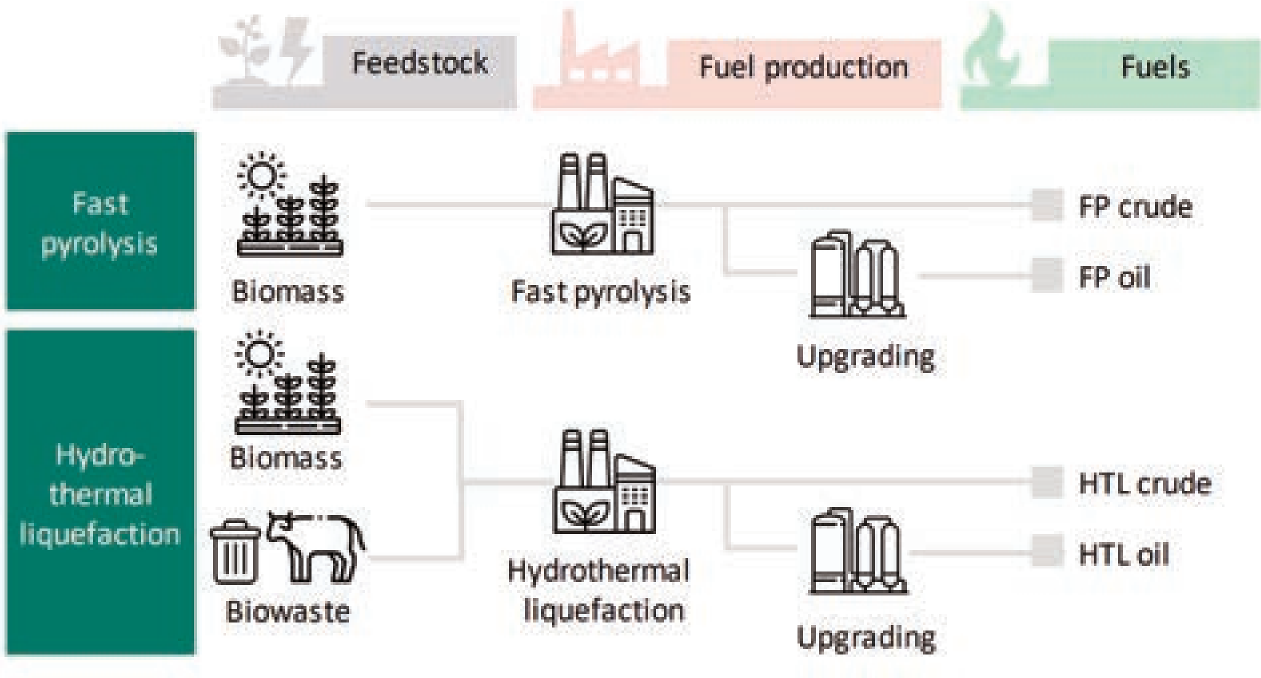
|Figure 2-2| Fischer-Tropsch fuel manufacturing process[11]

2.1.4 FP bio oil

Fuel produced by heating biomass with high-temperature (400-600℃) inert gases, which contain little to no oxygen and have a high nitrogen content, under atmospheric pressure through a process called rapid thermal pyrolysis is known as FP bio crude. This crude oil, as shown in Table 2-1, is upgraded to become fast-pyrolysis bio-oil. Both woody and waste biomass resources can be used as feedstock in this process.[9,10] Currently, crude FP is used for regional heating and as an industrial energy source, while technology for upgrading it to oil is still under development. Although this fuel is expected to be more expensive than VLSFO, it is also anticipated to be cheaper than hydrothermal liquefaction bio-oil.[12]

2.1.5 Hydrothermal liquefaction bio oil

Biomass, crushed to an appropriate size and mixed with water, is fed into a reactor where it is transformed into a liquid biofuel under high temperature (250-550℃) and high pressure (5-25 MPa) conditions. Unlike fast-pyrolysis bio-oil, this biofuel has the advantage of utilizing biomass with high moisture content as feedstock. Similar to fast pyrolysis crude (FP crude), hydrothermal liquefaction crude oil (HTL crude) can be upgraded to hydrothermal liquefaction bio oil through processes like hydrogen addition. However, these upgraded technologies are still under development.[12]



|Figure 2-3| Fast pyrolysis and hydrothermal liquefaction bio crude/oil production process[12]

2.1.6 Bio heavy oil

Bio-heavy oil, made from underutilized resources, such as pitch (a by-product of the biodiesel production process), animal fats, oil extracted from food waste, and palm by-products, is utilized by domestic shipping companies. These companies have blended this fuel for use in generator engines and have successfully completed demonstrations at sea.[13]

2.2 Classification according to biofuel feedstocks

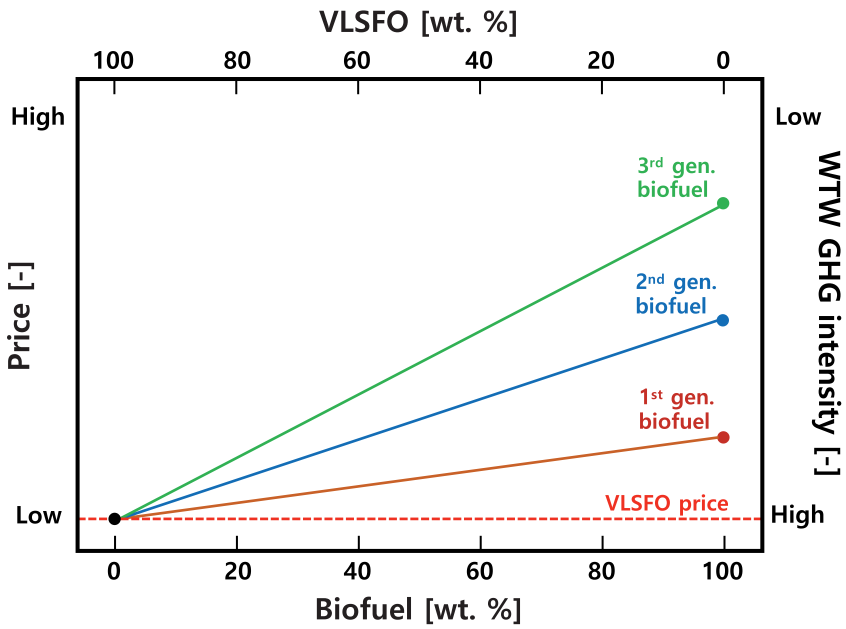
Biofuels can be categorized into several generations based on their raw materials, as indicated in table below.

This classification is essential for understanding the environmental and socioeconomic impacts. The research and development of fourth-generation biofuels that utilize various technologies, including carbon dioxide storage and capture during the biofuel production process, are ongoing. With advances in technology, biofuels continue to evolve into promising and sustainable alternatives to fossil fuels.

|Table 2-3| Biofuel classification and characteristics according to classification

Classification	Feedstocks	Characteristics
1st generation biofuel	Corn, palm, soybean, sugar cane, etc.	- Potential for competition over arable land between food and fuel crops, risking higher prices and food shortages - Indirect land use changes like converting pastures and farmlands for raw material production may cause deforestation and elevate greenhouse gas emissions
2nd generation biofuel	Waste cooking oil, agricultural residues, forestry residues, animal fat, biomass waste, etc.	- Environmentally friendlier by not utilizing food resources - Aids in waste management by utilizing waste resources
3rd generation biofuel	Microalgae, microorganisms, etc.	- Grown on non-cultivated land, avoiding impact on food production - Energy production per unit area is higher due to algae's rapid growth - Large-scale commercial production challenging due to technical and economic factors

The costs and GHG emissions of biofuels vary depending on their generation. As shown in Figure 2-4, biofuels are priced higher than conventional VLSFO fuels, and their prices increase with increasing blending ratios. Additionally, as fuel generation advances, the price increase tends to be steeper, while the entire lifecycle (WtW) of GHG emissions shows a decreasing trend. For instance, ships rated D or E under the IMO's Carbon Intensity Indicator (CII) may need to use biofuels that are more expensive, but have lower WtW GHG emissions, to improve their performance. Although the conversion to alternative fuel-powered ships is an option, some shipping companies may lack the economic means and time necessary for such conversions.

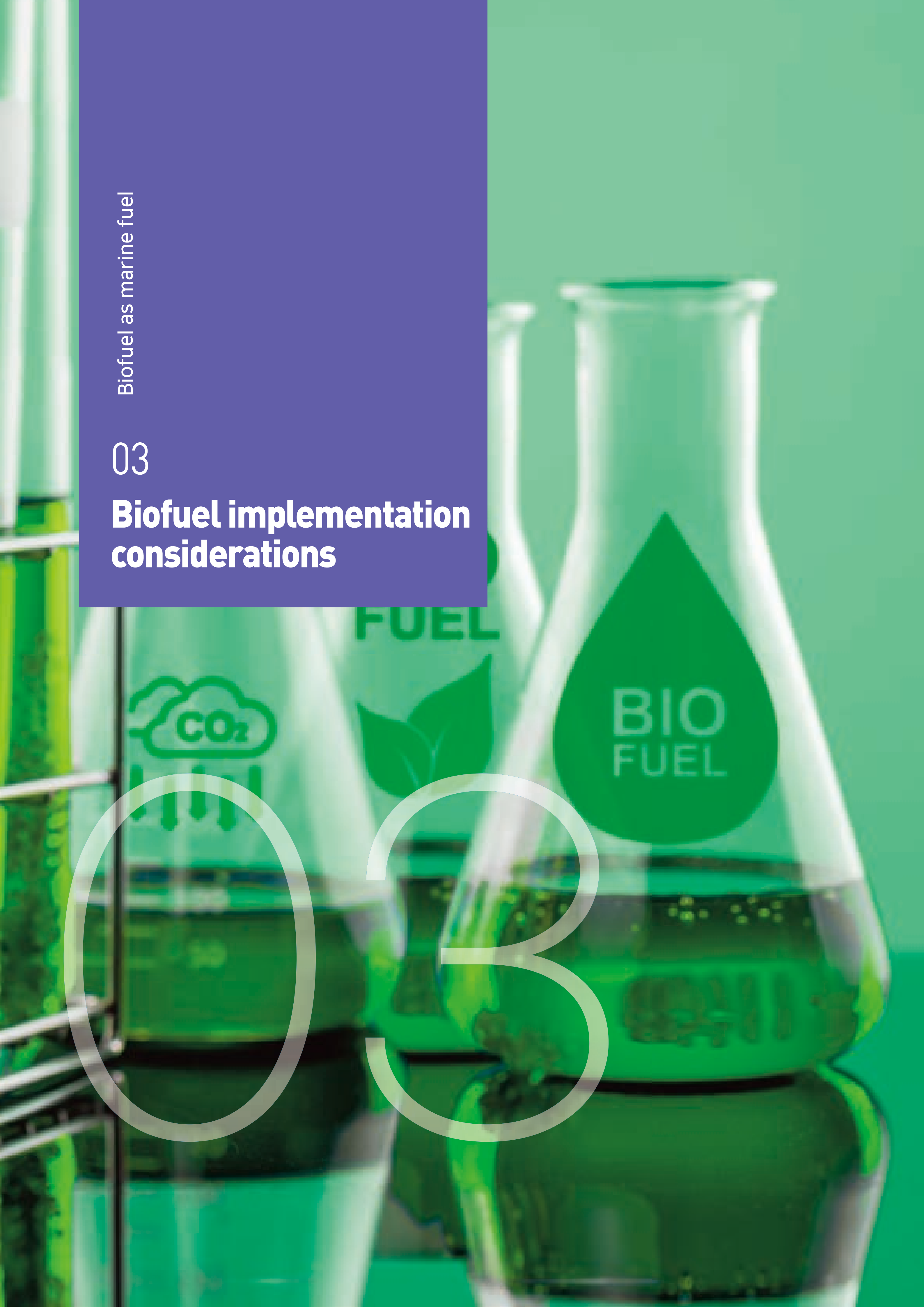


|Figure 2-4| Comparison of price and WTW greenhouse gas intensity according to biofuel generation classification

To understand the regulatory response to biofuels, Section 6.2 will provide a detailed examination of the impact of biofuel application on CII ratings using a hypothetical ship case study.

03

Biofuel implementation considerations



3.1 Biofuel quality standards

Currently, international standards for biofuels usable in ships are limited to quality standards for fuels blended with 7 v/v% FAME and distillates. The International Council on Combustion Engines (CIMAC) also provides guidelines for this purpose.[14] It is anticipated that amendments to ISO 8217 will include additional requirements for biofuels and their blends with traditional fuels. However, there is an urgent need to develop international standards that support biofuel usage and bunkering to accelerate the transition to carbon neutrality. Recognizing this urgency, Singapore developed and adhered to a national standard, allowing marine biofuel blends of up to 50 v/v% or m/m%, preceding the establishment of international standards.[15] As for HVO fuel is not currently specified in any marine fuel standard, as shown in Table 3-1, there are existing standards for paraffinic diesel fuel used for land transportation.

|Table 3-1| Comparison of properties of FAME and HVO[16]

Property	FAME			HVO		
	Min	Max	Standard	Min	Max	Standard
Cetane number	51	-	EN 14214	70	-	EN 15940
Density@ 15℃[kg/m³]	860	900	EN 14214	765	800	EN 15940
Flashpoint[℃]	101	-	EN 14214	55.1	-	EN 15940
Viscosity@ 40℃[mm²/s]	3.5	5.0	EN 14214	2.0	4.5	EN 15940
Lubricity[μm]				-	400	EN 15940
Aromatics[%(m/m)]				-	1.1	EN 15940
Sulphur content[mg/kg]				-	5.0	EN 15940
Carbon residue on 10% distillation residue[% (m/m)]				-	0.1	EN 15940
Sulphated ash content[%(m/m)]	-	0.02	EN 14214	-	0.001	EN 15940
Water content[% m/m]	-	0.05	EN 14214	-	0.02	EN 15940
Total contamination[mg/kg]	-	24	EN 14214	-	24	EN 15940
Oxidation stability@110℃[h]	8.0	-	EN 14214	-	25	EN 15940
Acid value[mg KOH/g]	-	0.5	EN 14214	-	0.01	EN 15940

3.2. Potential engine operation issues and countermeasures

While maritime demonstrations of biofuel use in ships are underway, establishing a standardized response is challenging because of various issues that can arise from the feedstock, type, and blending ratio of biofuels. Additionally, most sea trials conducted by shipping companies are short term and limited to small quantities of biofuels or blends, increasing the likelihood that problems may not have been observed. However, as global and regional GHG regulations become more stringent, and shipping companies increasingly consider or apply biofuels, there is a growing need to be aware of and prepare for issues that may arise during long-term use. Therefore, this section explains the potential problems that can occur with the use of biofuels in ships and introduces countermeasures to address them.

3.2.1 Microbial growth

FAMEs are highly hygroscopic and can lead to microbial contamination of fuel during long-term storage.[2] Moisture in the fuel and tank can create optimal conditions for microbial growth, potentially causing sludge formation and clogging of filters or pipes.[9] Therefore, the quick use of small quantities of FAME fuel or blends is recommended. For long-term use or storage, monitoring is necessary to maintain appropriate fuel and tank temperatures, and removing moisture from the tank can reduce the risk of microbial growth.[9] While the use of biocides or additives is generally not recommended because of the potential environmental and human health risks,[16] caution is advised when considering their use.

Conversely, HVO can be stored and handled similarly to conventional fuel oils, and, unlike FAME, exhibits less microbial growth than conventional fuel oil. However, because of their lower densities, adjustments to the separators may be required for efficient moisture removal.[16]

3.2.2 Oxygen stability

Fuel oxidation stability is an indicator of the ability of a fuel to resist oxidation during storage and use. The presence of unsaturated compounds in FAME increases the likelihood of oxidation. These unsaturated compounds readily react with dissolved oxygen to form peroxides, which can decompose and react with acids to form other compounds as the oxidation progresses.[9] These compounds can lead to the clogging of filters, separators, and fuel injection systems, requiring caution. Additionally, the acidic components produced during oxidation can corrode fuel system components, potentially damaging fuel pumps, piston rings, and injectors.

There are various methods to improve the oxidation stability, one of which is the addition of antioxidants. However, there have been no reported cases of antioxidants being added to the fuel supplied to ships.[9] In addition, certain metal ions can accelerate oxidation; therefore, attention must be paid to the material selection of the components.

3.2.3 Cold flow properties

The viscosity of all fuels changed with temperature, and the viscosity of FAME was also temperature-dependent. In particular, under low-temperature conditions, FAME exhibits poor fluid characteristics, and both the Wax Appearance Temperature (WAT) and Wax Disappearance Temperature (WDT) can vary depending on the raw materials or mixtures, thus requiring proper temperature control.[16] The CIMAC recommends maintaining a fuel temperature at least 10°C higher than its pour point.[17] However, temperatures that are too high can lead to the formation of carbonaceous polymers, so it is advised not to exceed 40°C above the pour point.[18]

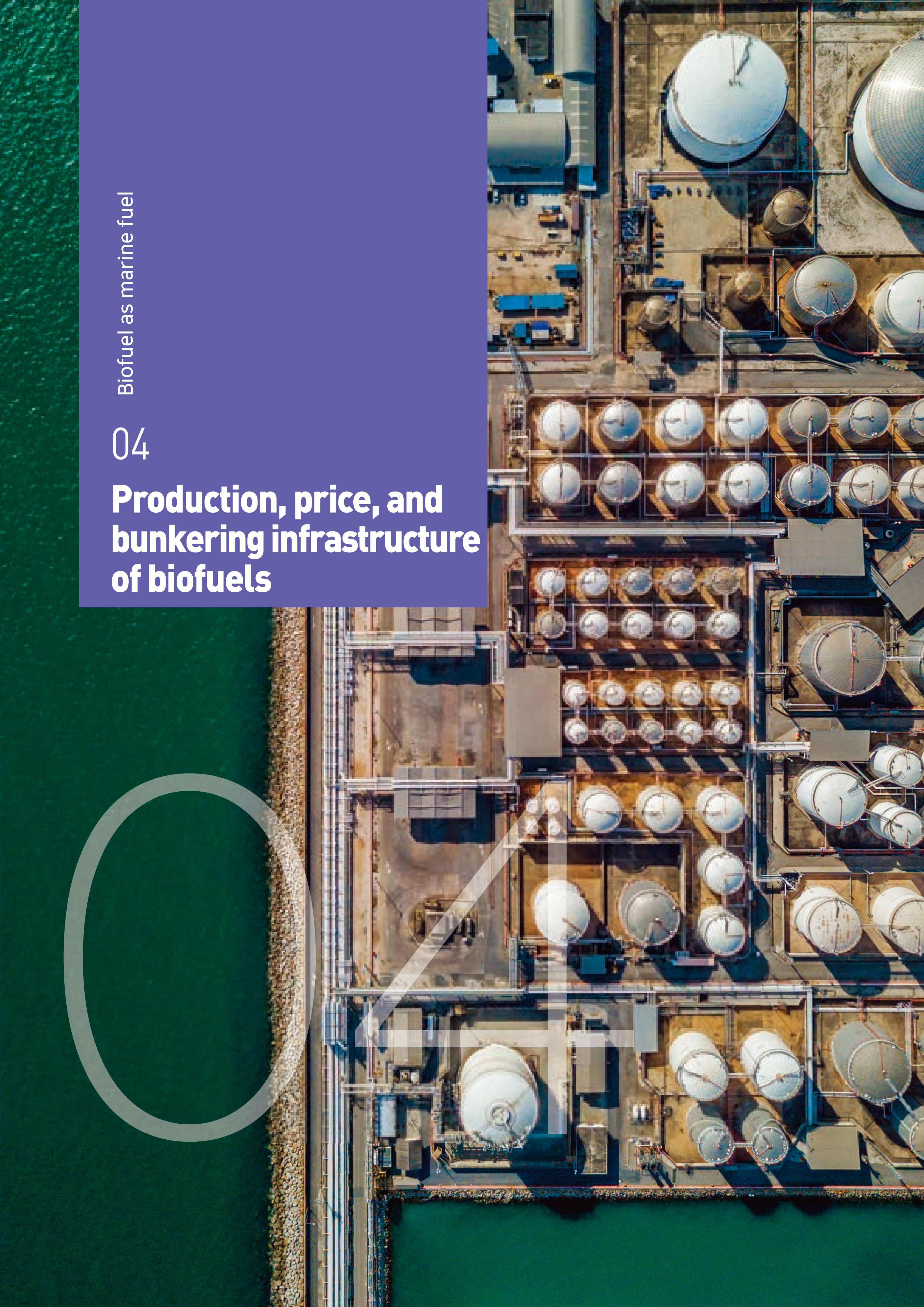
Therefore, before using biofuels or blended fuels, it is necessary to check the viscosity, pour point, WAT, and WDT and store the fuel appropriately. The use of additives can also be a solution.

3.2.4 Material compatibility with metals, seals, gaskets, and polymers

Certain metals such as copper, brass, lead, tin, and zinc can accelerate the oxidation of FAME fuels, potentially leading to increased sediment formation.[19] Exposure to FAME fuels can also cause seals and gaskets to swell or degrade, potentially leading to equipment leaks or malfunctions. The same can occur with polymers; therefore, it is important to verify this with equipment suppliers before using these fuels.[10]

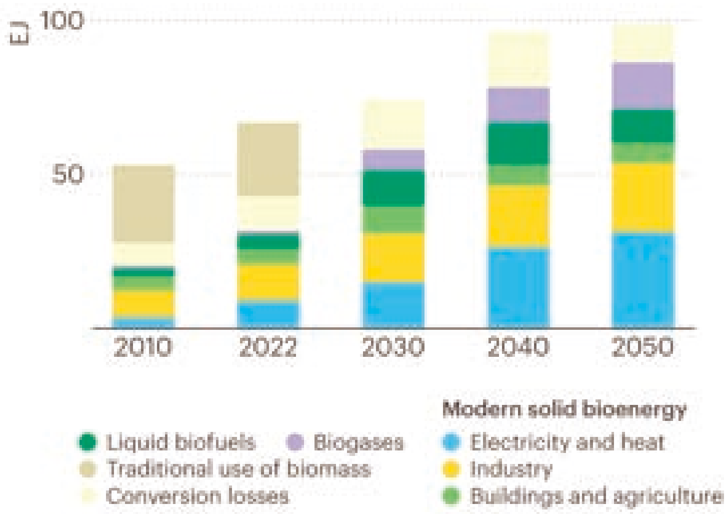
04

Production, price, and bunkering infrastructure of biofuels

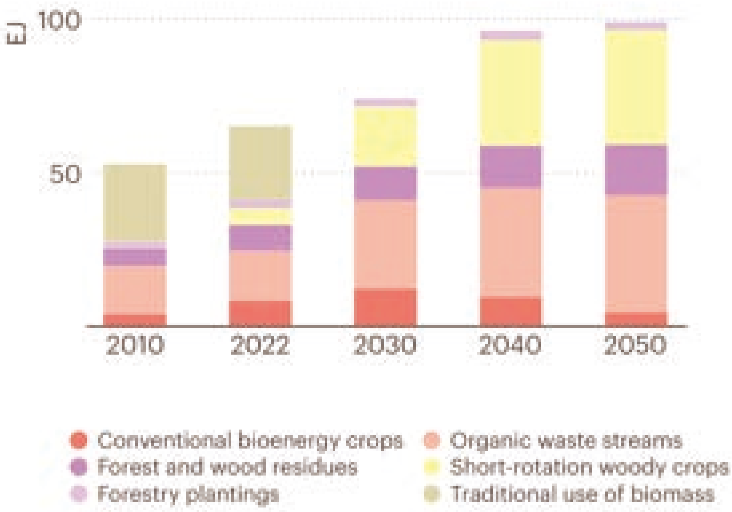


4.1 Biofuel production

Bioenergy, which can directly replace fuels based on fossil fuels, is currently used in nearly all industrial sectors worldwide. The International Energy Agency (IEA) forecasts[20] that by approximately 2050, ~1.5 times more bioenergy will be needed than in 2022 based on energy units. Furthermore, as shown in Figure 4-1(b), to achieve carbon neutrality, it is expected that more bioenergy will be produced from waste resources, woody biomass, and other materials, which can reduce the carbon footprint compared to bioenergy made from traditional raw materials.



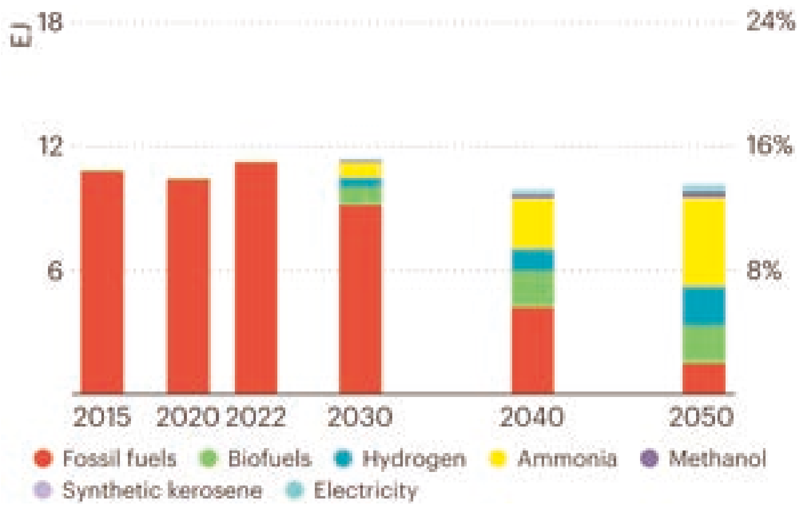
(a) Demand for bioenergy



(b) Supply of bioenergy

|Figure 4-1| Bioenergy demand and supply outlook[20]

In the maritime sector, as shown in Figure 4-2, among the consumed energy sources, it is expected that the current share of bioenergy, hydrogen, and hydrogen-based fuels of less than 1% will increase to nearly 15% by 2030 and up to 80% by 2050. Ammonia and hydrogen fuels are primarily used as raw materials and the use of biofuels is expected to continue to increase.[20] While the proportion of these fuels may vary depending on regulations related to GHGs, fuel price, and the level of technological development, the use of carbon-free fuels is essential for achieving carbon neutrality in the maritime sector, and biofuels will also play an important role.[20]



|Figure 4-2| Forecast of energy consumption in the shipping sector[20]

When compared across different modes of transportation, as shown in Table 4-1, the use of biofuels in all modes of transportation is predicted to increase continuously until reaching a peak around 2040. In relation to the strengthening of GHG regulations, the IEA anticipates that as internal combustion engines are gradually phased out in the land transportation sector, the demand for biofuels in road transportation will decrease and the use of fuels for maritime and aviation purposes will increase.

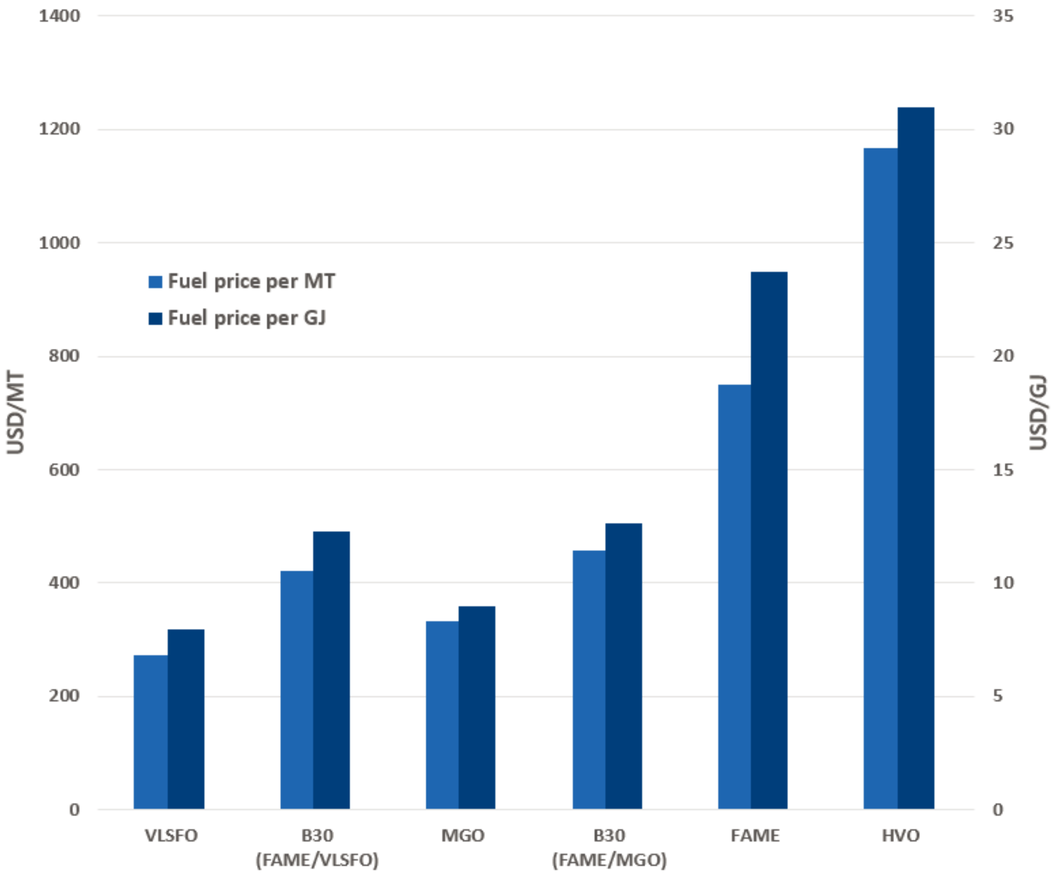
|Table 4-1| Predicted biofuel usage proportions by transportation sources[20]

Sectors	2022	2030	2034	2050
Biofuels share in road sector	5%	11%	12%	3%
Biofuels share in shipping	0%	8%	13%	19%
Biofuels share in aviation	0%	10%	22%	33%

The transition towards carbon neutrality across all industries can trigger competition for sustainable biomass and biofuels, implying that the availability of biofuels in the maritime sector could be limited.[21]

4.2 Biofuel price

Figure 4-3 presents a comparison of the prices per unit mass and biofuel energy. Compared to VLSFO, the price of FAME was found to be approximately three times higher, and the price of HVO was approximately 3.9 times higher. Thus, fuels blended with biofuels and traditional fossil fuels are expensive.[16]



|Figure 4-3| Comparison of Biofuel and Blended Fuel Prices (as of March 2021) [16]

For the fuel price survey benchmark (March 2021), the price of FAME is about 23 USD/GJ. According to the price predictions for alternative fuels by the Maersk McKinney Moller Center (MMMC)[18], in 2030, the price is expected to be around 22 USD/GJ, and by 2050, about 23 USD/GJ, indicating no significant change in the price of biofuels.

The price of biofuels can fluctuate based on raw materials and manufacturing processes and may vary over time owing to supply and demand dynamics. The biomass used for producing biofuels is slated for expanded use not only in transportation, but also across all industrial sectors. The limited availability of raw materials and competition from other industries may lead to an increase in biofuel prices. Therefore, the continuous monitoring of biofuel prices in the future is necessary.

|Figure 4-4| Prices of various alternative fuels (considering the application of carbon pricing at 230 USD/tCO2-eq)[21]

4.3 Bunkering infrastructure

Biofuels can be produced globally; however, the infrastructure for bunkering biofuels is currently limited. However, as GHG regulations become stricter, the demand for and usage of biofuels as sustainable fuels from a life-cycle perspective is increasing, which is expected to lead to more ports being capable of bunkering. Additionally, 'drop-in' biofuels, which are compatible with existing fossil fuels, could utilize existing bunkering infrastructure without significant new investment. The major bunkering ports were Antwerp, Rotterdam, Amsterdam, Singapore, Fujairah, and Gothenburg.

However, for ship-to-ship (StS) biofuel bunkering, limitations on biofuel blend ratios and construction standards for bunkering vessels according to the IMO's IBC Code (International Code for the Construction and Equipment of Ships Carrying Dangerous Chemicals in Bulk) may pose obstacles in the initial journey towards carbon neutrality through biofuels. Discussions on solutions are expected to commence at the MEPC 81st meeting of the IMO.

05

Regulatory considerations for biofuel

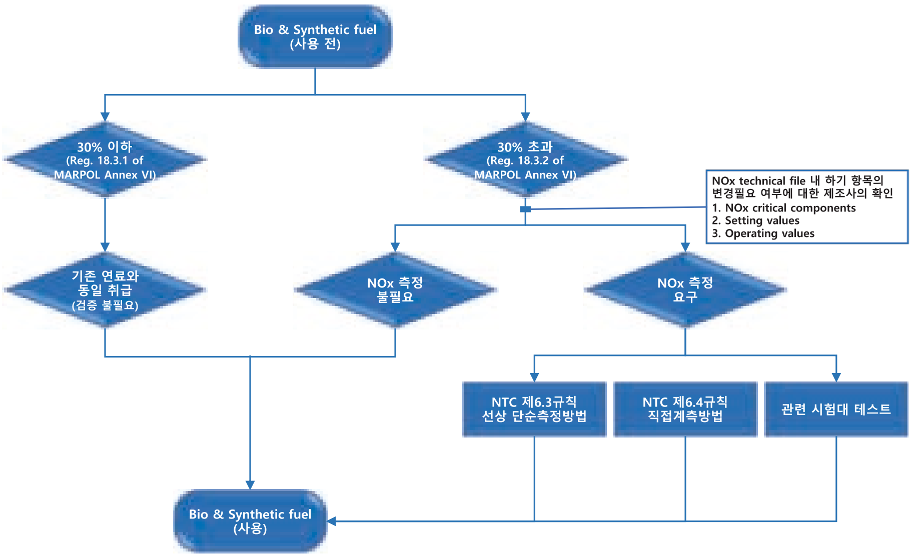
5.1 Air pollutants

The major air pollutants emitted from ships include nitrogen oxides (NOx), sulfur oxides, and particulate matter, which are generated during the combustion process of internal combustion engines used for the main propulsion and power generation of ships and are discharged into the atmosphere. These air pollutants have significant environmental and human health impacts. Therefore, their emissions are regulated through various rules in Annex VI of the IMO Marine Pollution Prevention Convention (MARPOL).

Even with the use of alternative fuels with low or no carbon content to achieve net-zero shipping, the emission of air pollutants is still expected. Although alternative fuels can reduce air pollutants, the physical properties and combustion characteristics of each fuel differ. Therefore, compliance with air pollutant regulations must be ensured prior to the use of alternative fuels.

5.1.1 Nitrogen oxides

When using fuel oil derived from methods other than petroleum refining or fuel oil blending of more than 30% biofuel by volume, there is a regulation that the emissions of nitrogen oxides (NOx) must not exceed the limits. Therefore, when using biofuels, verification of NOx emissions onboard must be conducted or approval must be obtained from the administration in accordance with Rule 3.2 of Annex VI of MARPOL. In the latter case, the Korean Register cooperated with shipping companies, engine manufacturers, and biofuel associations to conduct both land and sea demonstrations of biofuel blends in accordance with the exemption regulations, and the results were shared externally.[22]



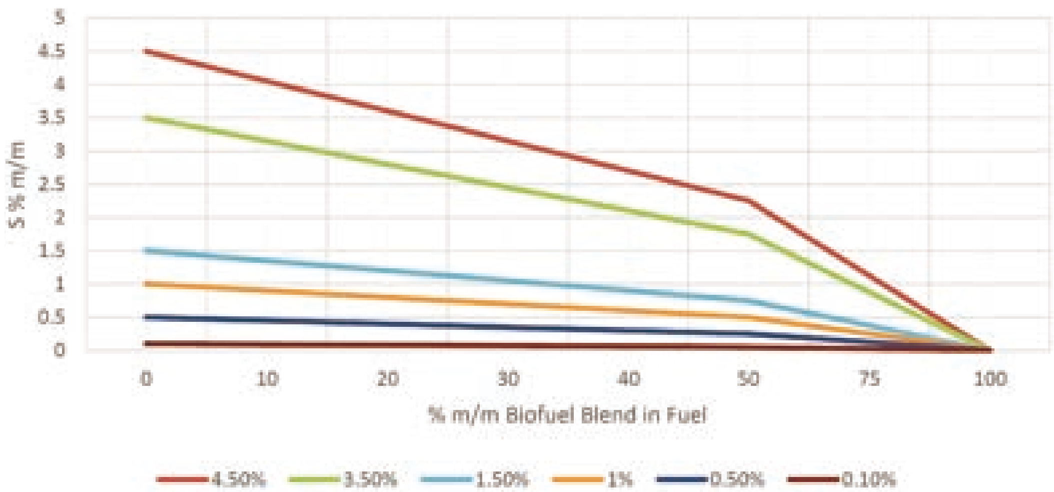
|Figure 5-1| NOx verification flowchart for use of biofuel or its blends [23]

Recently, as various alternative fuels have been considered to reduce GHG emissions, biofuels have gained attention as the simplest and most effective immediate alternative for carbon reduction in the shipping industry. However, the previously mentioned nitrogen oxide (NOx) regulations are obstacles to the use of biofuels.

The IMO approved an agenda[24] at the 78th meeting of MEPC, which included a unified interpretation of Regulation 18.3 in Annex VI of MARPOL, to accelerate the transition to net zero. Consequently, as illustrated in Figure 5-1, internal combustion engines using biofuels blended up to 30% can now be used without the need for onboard NOx verification procedures. However, for biofuel blends exceeding 30%, verification is required after conducting onboard simple measurement methods, direct measurement methods, or relevant land-based tests, according to the NOx Technical Code 2008. Nonetheless, a separate verification is not necessary if the engine manufacturer confirms that its use is possible without changes to the key components, settings, and operational values related to nitrogen oxide emissions.

5.1.2 Sulfur oxides and particulate matter

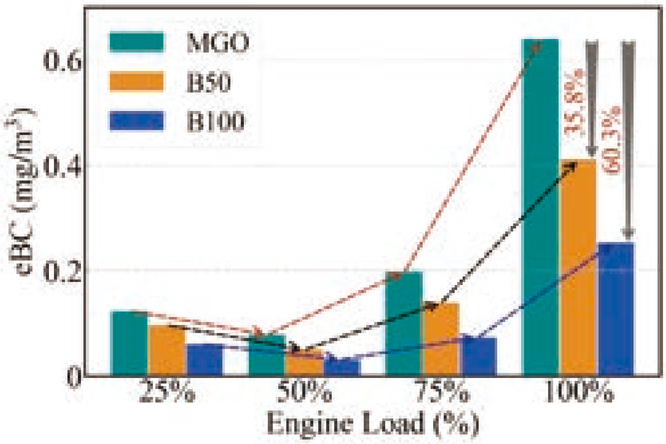
The IMO regulates the emissions of sulfur oxides and particulate matter through Regulation 14 of Annex VI of the International Convention for the Prevention of Pollution from Ships (MARPOL). The regulation of the sulfur content in fuels limits the emission of sulfur oxides. As shown in the figure, the sulfur content of the biofuel blends decreased with an increase in the biofuel mixing ratio. If biofuels completely replace conventional fuels, the sulfur content approaches zero. In other words, increasing the biofuel blend ratio can reduce sulfur oxide emissions, and complete replacement can effectively eliminate these emissions.



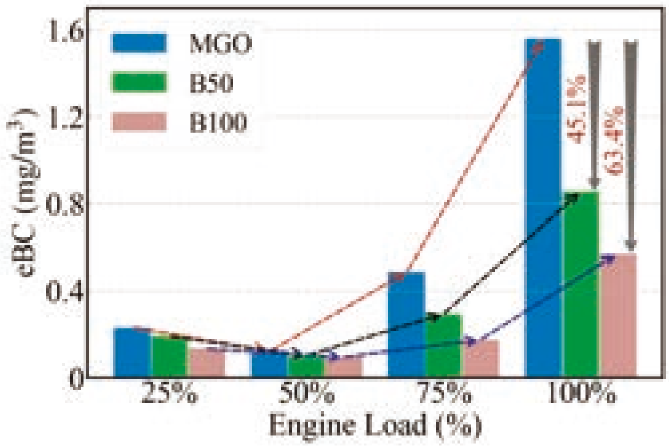
|Figure 5-2| Prediction of sulfur content of biofuel blends according to sulfur content of fuel oil and biofuel mixing ratio [10]

Particulate matter emissions are indirectly limited through the regulation of the sulfur content in fuel. Biofuels such as FAME contain oxygen elements within the fuel, improving combustion efficiency and consequently reducing particulate matter emissions. In the Arctic region, discussions are ongoing to regulate black carbon as an atmospheric pollutant, and its reduction through increased biofuel blend ratios has been observed.

The Filter Smoke Number (FSN) and photoacoustic measurements are among the most prominent methods for measuring black carbon.[25] Using these methods, the effects of biofuels on black carbon reduction were measured using a slow-speed engine (RXT8, 8,916 kW).[26] The results, as shown in Figure 5-3, indicate that at maximum output conditions (100% load), a blend of 50% MGO and 50% biodiesel showed a reduction characteristic of 35.8-45.1%, whereas pure biodiesel use resulted in a reduction rate of 60.3-63.4%. Therefore, the blending or substitution of biofuels can be considered an effective alternative for reducing particulate matter and black carbon emissions.



a)Black carbon emission measured by FSN method



b)Black carbon emission measured by photoacoustic method

|Figure 5-3| Comparison of black carbon emission of the engine when using different fuels with both measurement methods[26]

5.2 IMO's Data Collection System (DCS) and CII related matters

At the 80th meeting of IMO MEPC, provisional guidelines[27] for the use of biofuels, which can be relatively easily utilized in existing ships, were approved. According to these guidelines, only biofuels that meet sustainability criteria through an international certification system and reduce carbon intensity by more than 65% compared to the WtW carbon intensity of fossil fuels (94gCO_{2eq}/MJ) can calculate their CO_2 conversion factor by multiplying the lower heating value by their full lifecycle carbon intensity. Fuels that do not meet the carbon intensity criteria are subject to the CO_2 conversion factor of fossil fuels. For biofuel blends, the CO_2 conversion factor is calculated as a weighted average. The method for calculating the conversion factor for biofuels can be referred to in the following example:

WtW GHG intensity: 26.48 gCO_{2eq}/MJ

LCV: 37.5 MJ/kg

$CF_{biofuel}$ = 26.48 gCO_{2eq}/MJ × 37.5 MJ/kg / 1000 = 0.993 gCO_{2eq}/MJ

Therefore, biofuels that have been verified through 3rd body certification systems, such as International Sustainability and Carbon Certification (ISCC) and Roundtable on Sustainable Biomaterials (RSB), and have a carbon intensity not exceeding 33gCO_{2eq}/MJ can be considered certified sustainable. To report under the DCS and receive a CII rating in the year following the use of biofuels, the following documents must be submitted: 1) a sustainability certificate (including WtW GHG intensity value), 2) a Bunker Delivery Note (BDN) to verify the quantity of biofuel, 3) documentation to verify the lower heating value, and 4) data for the calculation of biofuel usage.

However, notably, these provisional guidelines approved at the 80th MEPC meeting are set to be phased out once GHG emission levels are established according to the Guidelines on life cycle GHG intensity of marine fuels (LCA guidelines).

5.3 EU regulation

In July 2021, the European Union announced the 'EU Fit for 55' package, a legislative framework aimed at reducing GHG emissions by 55% by 2030 compared to 1990 levels. Two major regulations have been introduced in the maritime sector: the Emission Trading System (ETS) and FuelEU Maritime.

The EU ETS is a system in which emission allowances are bought and sold based on the amount of GHG emissions, and is scheduled to be applied to the maritime sector starting in 2024. The key aspect of this regulation is that ships must purchase emission allowances for GHGs emitted while entering or operating EU ports. In 2024, allowances covering 40% of the emissions will be required, 70% by 2025, and 100% from 2026 onwards. Biofuels, recognized as sustainable fuels under the EU's Renewable Energy Directive (RED), can have their emission factors set to zero, thus not only facilitating compliance with IMO regulations but also promoting their use under EU regional regulations.

Starting in 2025, FuelEU Maritime mandated the use of eco-friendly fuels in ships and imposed fines on those who did not comply. It sets the WtW GHG intensity every five years, aiming for an 80% reduction compared with the standard carbon intensity by 2050. While blending biofuel can lower the WtW carbon intensity, compliance with the regulations depends on the WtW carbon intensity of the biofuel used. Therefore, to meet both global (IMO) and regional (EU) regulations, selecting and blending or substituting biofuels with low WtW carbon intensity is necessary.

From a long-term perspective, considering the possibility of fines, emissions trading systems, or carbon taxes being introduced in both IMO's- and long-term measures and EU regulations, shipping companies will need to develop economic capacity to respond to these challenges.

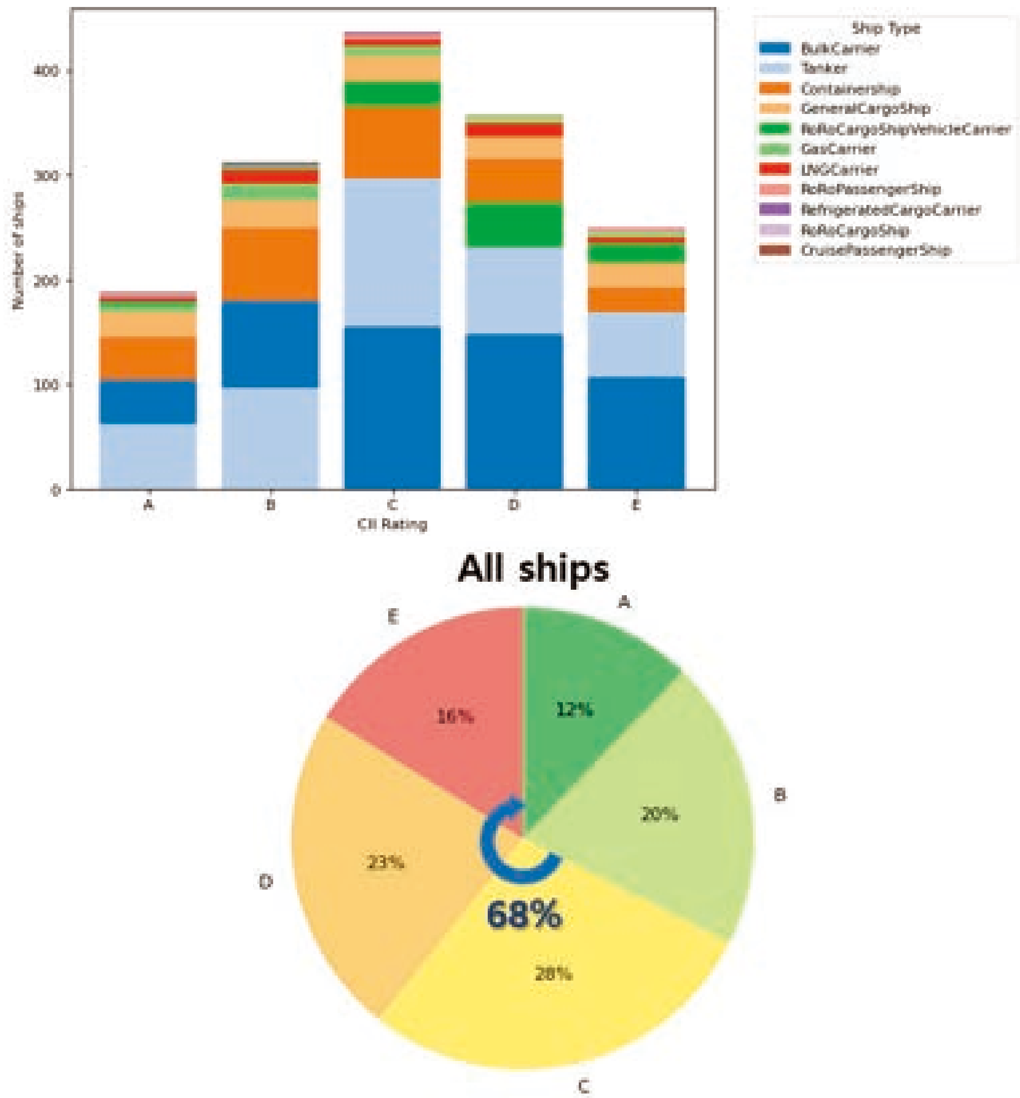
06

Biofuel in the context of CII compliance

6.1 CII rating status[28]

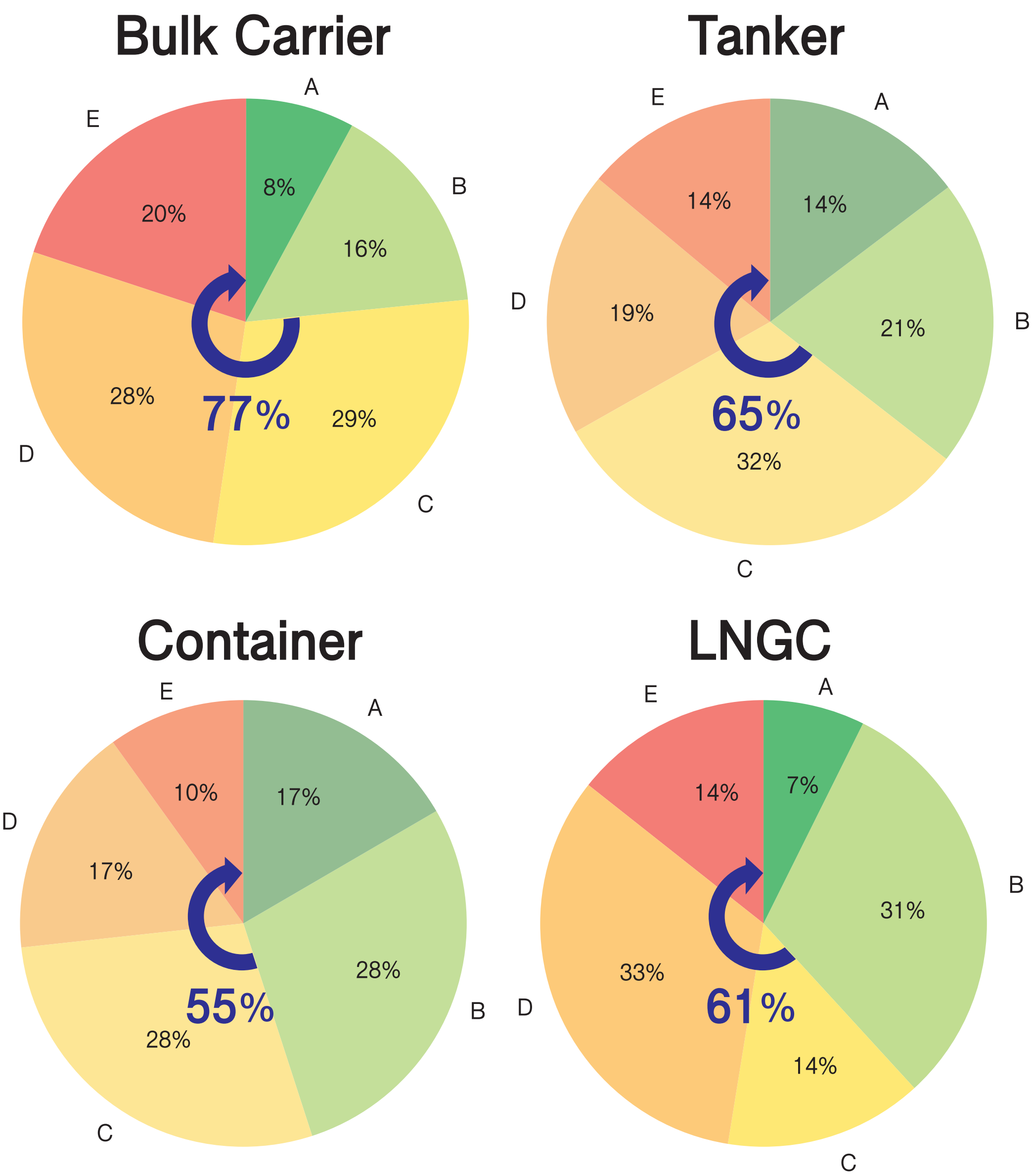
Since 2023, CII regulations have been applied to ships with over 5,000 GT engaged in international voyages, including those covered under Regulation 26.3 of MARPOL Annex VI. Consequently, shipping companies are focusing on the anticipated CII rating results for their vessels.

In this context, to provide shipping companies with advance information on their CII ratings, a preliminary analysis of the CII ratings based on 2022 DCS data was conducted. Approximately 2,000 vessels' IMO DCS data for 2022 were submitted using KR GHG Emission, Authentic Reporting System (GEARs) and verified. Based on this, a preliminary analysis of their CII ratings was conducted, and the results are shown in the graph below.



|Figure 6-1| Analysis results of CII ratings by ship type

An analysis of the distribution of CII ratings by ship type in terms of the number and proportion of ships revealed that 16% of the total ships were rated E, 23% were rated D, and approximately 28% were rated C. This reveals that ships rated C-E account for ~68% of the total. Given that the CII allowance values are becoming stricter each year, and considering the possibility that ships currently rated C could be downgraded to D or E in the future, it is evident that not only ships rated D or E but also those rated C need to consider and implement appropriate measures to improve their CII ratings.



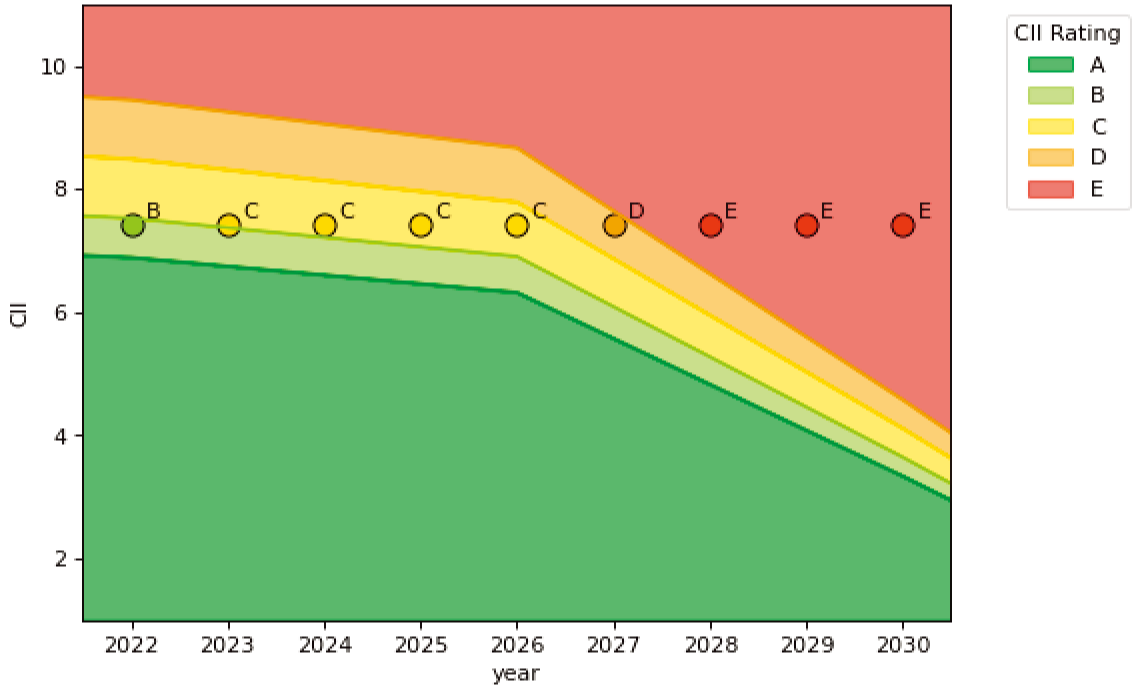
|Figure 6-2| Comparison of CII rating distribution ratios by ship type

The CII rating percentages for the four ship types (bulk carriers, tankers, container ships, and LNG carriers) submitted to our classification society are shown in Figure 6-2. For bulk carriers, the proportion of ships rated C to E was relatively high at 77% of the total fleet, whereas container ships had a lower proportion of 55% with the C-to-E rating, below the overall average of 68%.

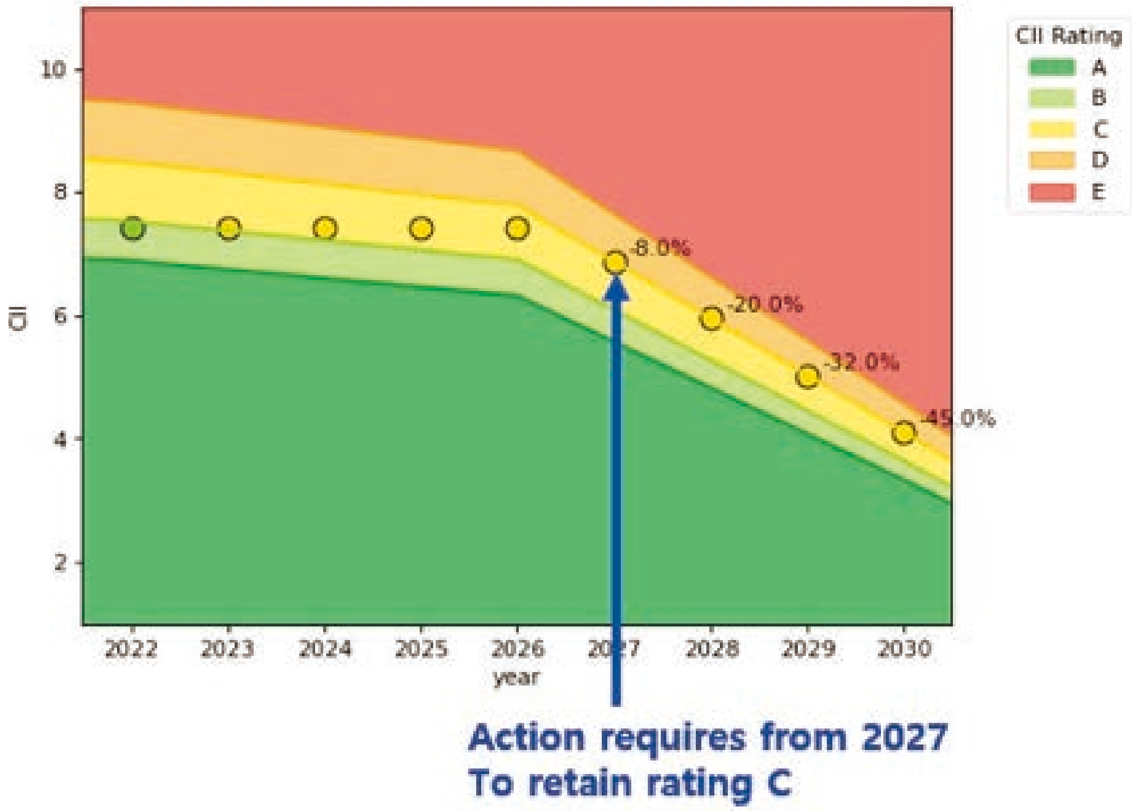
Bulk carriers and tankers, which have a higher proportion of tramp shipping than the regular line operation of container ships, have longer waiting times, leading to a higher percentage of lower CII ratings. LNG carriers, many of which use less efficient steam turbines for propulsion, had 61% of their ships rated between C to.

Let us now examine the results of the data analysis for a specific ship. A handy-size bulk carrier was selected from the total fleet, which achieved a B rating based on the 2022 standards. Assuming a yearly reduction rate of 2.75% from 2027 to 2030, based on the goal maintained at the 80th MEPC meeting to reduce carbon intensity by 40% by 2030 compared to 2008, we analyzed the expected CII ratings post-2023 in the graph below. The upper part of the graph shows the rating changes up to 2030 if no CII rating improvement measures are taken, and the lower part shows the GHG reduction percentage required to maintain at least one C rating.

It is projected that this ship will maintain a C rating from 2023 to 2026, downgrade to D in 2027, and change from D to E in 2028. Therefore, as shown in Figure 6-3, it is evident that improvement measures are required by 2027 to maintain at least the C-rating.



a) Expected CII rating without improvement measures



b) CII improvement rate required to maintain a C grade

|Figure 6-3| Annual projected CII ratings for a specific vessel

Shipping companies can take the following measures to improve the CII rating of their existing vessels: Firstly, they can reduce the speed of the ship. This involves decreasing speed to the lowest feasible limit in terms of business and operational aspects. Additionally, this can be implemented in conjunction with other measures such as speed and route optimization through weather routing, ensuring just-in-time arrivals, maintaining optimal trim, periodic propeller and hull cleaning, and using shore power.

Secondly, energy efficiency can be improved by applying technologies that reduce vessel resistance and enhance propulsion efficiency. These include the application of low-friction paint or coatings, replacing propellers to match the reduced speeds, and installing energy-saving devices (ESD). A careful approach is required to consider the uncertainty of the GHG reduction effects of these devices and the associated CAPEX and OPEX.

Finally, a transition to alternative fuels with significant GHG reduction effects should be considered. One feasible initial option is the use of biofuels. Recently, at the 80th MEPC meeting of the IMO, provisional guidelines[27] were approved for the use of biofuels in relation to Regulations 26, 27, and 28 of MARPOL Annex VI (DCS and CII aspects). The use of biofuels that satisfy the criteria outlined in these guidelines can achieve GHG emissions. However, the uncertainties of fuel supply and higher cost compared to conventional fuels must be considered.

The measures introduced herein are representative examples. It is advisable to review all possible actions and select appropriate combinations for each vessel. For instance, a strategy may include reducing speed and applying route optimization through weather routing, followed by the use of biofuel blends. In the case of biofuels, different blending ratios can be sourced and utilized, depending on the amount of GHG reduction required to comply with regulations.

6.2 Case Study - Perspective on CII regulation compliance

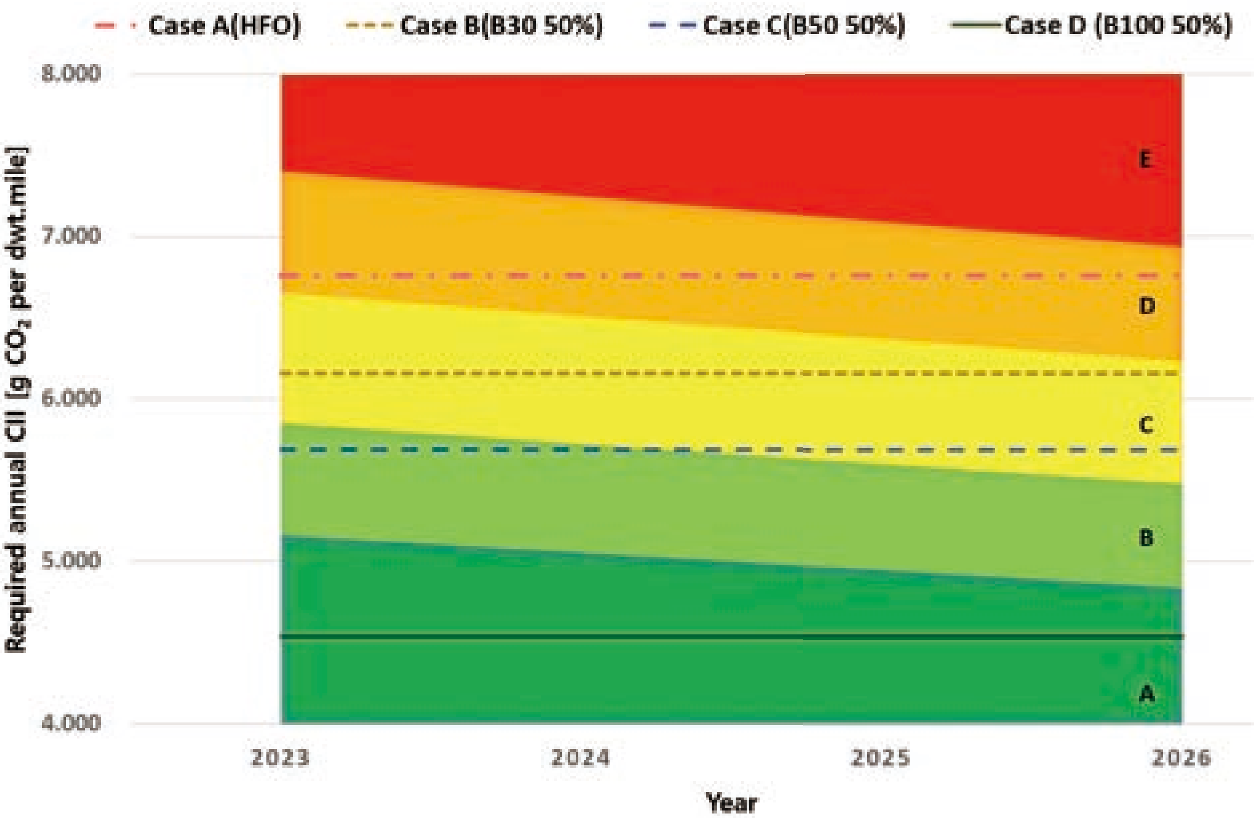
The transition from traditional fossil fuels to biofuels, or the application of biofuel blends, is the simplest and most immediately applicable alternative for shipowners in response to increasingly stringent GHG regulations. The approval of provisional guidelines on the use of biofuels at the 80th meeting of the IMO MEPC can be considered a measure of GHG reduction that considers the immediate applicability of biofuels.

In this section, we examine the degree of CII rating improvement through the application of biofuels and biofuel blends using a hypothetical container ship as an example, as shown in Table 6-1. This imaginary vessel is assumed to have fuel usage and operating distances, as outlined in the table below, and it initially uses HFO with a CII rating of D. The CII ratings for various fuels were calculated based on the annual emission ratio (AER) reduction rate set until 2026. When applying biofuels and biofuel blends, it was assumed that 50% of the existing fuel oil consumption would be replaced, and the ship would travel the same route and distance to analyze the improvement effect on the CII rating. The CO2 conversion factor for biofuels was the same as that used in the previous section (Section 5.2), and for the biofuel blends (B30 and B50), it was calculated using the weighted average of the fuel consumption.

|Table 6-1| Vessel information and types of fuel

Vessel Type	Vessel information	Fuel type
Container (10,000 teu)	Deadweight: 120,000 M/T Gross tonnage: 114,200 M/T Distance travelled: 70,000 nautical mile Fuel consumption (HFO): 18,240 M/T	Case A: HFO 100% (Base) Case B: B30(HFO 70 m/m%, Biofuel 30 m/m% Case C: B50(HFO 50 m/m%, Biofuel 50 m/m%) Case D: Biofuel 100%

* Assumptions: 1) The vessel travels the same route and distance; 2) for biofuels and blends, 50% of the fuel is replaced based on the mass usage of the existing fuel oil; 3) Biofuel WtW GHG intensity: 26.48 gCO2eq/MJ



|Figure 6-4| Comparison of CII ratings based on the replacement with biofuels and biofuel blends

As shown in Figure 6-4, if no measures are taken and the ship continues to operate on conventional fuel (Case A) from 2023, it is expected to maintain a D rating by 2026. However, if operated on fuel mixed with 30% biofuel (Case B), the ship could achieve a C rating by 2026. With a 50% biofuel blend (Case C), it is predicted that the ship will receive a B rating in 2023 and a C rating from 2024 onwards. If the ship completely switches to biofuel (Case D), it is expected to achieve an A-rating from 2023 to 2026.

|Table 6-2| Comparison of expected CII Ratings based on biofuel application

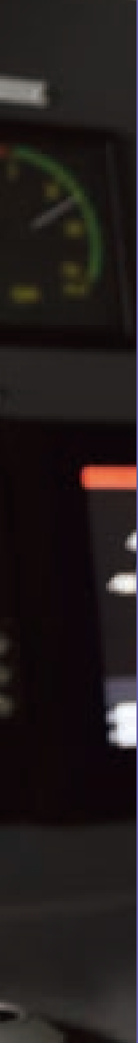
Rating year	2023	2024	2025	2026
Case A	D	D	D	D
Case B	C	C	C	D
Case C	B	C	C	C
Case D	A	A	A	A

Compared to using conventional fuel oil (Case A), using B30 improved the attained CII by 8.9%, B50 resulted in a 15.9% improvement, and complete switching to biofuel led to a 32.9% improvement in the attained CII.

These predicted results are for a hypothetical vessel and are based on assumptions about the characteristics of biofuels (WtW intensity and lower heating value); therefore, the actual improvement effects may vary from ship to ship. However, the use of biofuels or biofuel blends can be an effective short-term solution for compliance with GHG regulations.

Shipping companies can establish various strategies by verifying the GHG reduction effects of biofuels. For example, if a shipping company owns older vessels that are difficult to retrofit and have CII ratings of D or E, it could respond to GHG regulations in the short term by increasing the blending ratio of biofuel blends.

In vessels equipped with dual-fuel engines looking to slightly improve their attained CII and upgrade their rating, it is anticipated that the targeted attained CII can be achieved using a portion of biofuel blends during diesel-mode operation or by switching the pilot fuel to biofuel. As a real-life example, it has been reported that a gas carrier with an LPG dual-fuel engine successfully completed tests after bunkering ~200 tons of B30 (a blend of 70% MGO and 30% HVO) fuel for use as a pilot fuel. The fuel used had a WtW GHG intensity of 16gCO2eq/MJ, indicating an 83% greenhouse gas reduction compared to MGO and meeting the provisional criteria approved at the 80th MEPC meeting. In this case, compared to using VLSFO in the diesel mode, using LPG as the main fuel and B30 as the pilot fuel resulted in an approximately 20% reduction in GHG emissions.[29]



07

Technical support and cooperation related to biofuels

The Korean Register recognizes the importance of biofuels in responding to GHG regulations and has been continuously monitoring regulations and conducting research activities, including publishing a technical document[30] while the use of bio-blended fuels is not yet widespread. Subsequently, we established a cooperative system with shipping companies, engine manufacturers, and biofuel suppliers and successfully conducted a maritime demonstration using bio-blended fuel (bio-heavy oil 20% + VLSFO 80%) on a 13,000 TEU container ship.[13]

Additionally, since 2015, we have been offering technical services at our 'Greenship Test and Certification Center (TCC),' utilizing our engine test bench to evaluate the applicability of biofuels for main propulsion and generator engines. This service includes an analysis of the power characteristics, combustion characteristics, and exhaust gas emissions.

|Figure 7-1| Engine test benches within the center; top) slow speed diesel engine, middle) medium speed diesel engine, bottom) medium speed dual fuel engine

|Table 7-1| Engine specifications available at the KR's test and certification center

Items	Engine specifications		
	Slow speed diesel engine	Medium speed diesel engine	Medium speed dual fuel engine
Engine model	MAN-HHI 6S46MC	STX-MAN 27/38	HiMSEN 22 CDF
Engine type	2 stroke, T/C	4 stroke, T/C	4 stroke, T/C
Fuel	Mono fuel	Mono fuel	Dual fuel(LNG)
Cylinder number	6 cylinders	6	5
Bore × Stroke	460 × 1,932	270 × 380	220 × 330
Rating output	7,400 kW(129 rpm)	1,920 kW(750 rpm)	1,075 kW(900 rpm)

To analyze the combustion characteristics, we acquired and analyzed data such as cylinder pressure curves, peak pressure, and compression pressure using sensors capable of measuring pressure in the combustion chamber. To analyze the exhaust characteristics, we measured the major atmospheric pollutants in the exhaust gas, including nitrogen oxides (NOx), sulfur oxides (SOx), and unburned hydrocarbons. In particular, for nitrogen oxides, we provide information on emissions using a gas analyzer that meets the standards required by the NOx Technical Code (NTC) and a Coriolis-type mass flow meter. Additionally, we used measuring instruments equipped with the FSN and photoacoustic measuring methods[25,26] which are considered the standard methods for measuring black carbon, to observe the trends in black carbon changes due to the application of biofuels. In the case of four-stroke dual-fuel engines, the applicability of biofuels can be evaluated in diesel mode. In gas mode, we can analyze and provide results on the applicability, including combustion characteristics, exhaust emission characteristics, and GHG reduction effects, when biofuels are used as pilot fuel.

08

Summary

Biofuels are based on biomass and share characteristics with fossil fuels. Some fuels, such as FAME and HVO, can be used immediately in existing internal combustion engines without major component changes. As carbon-neutral fuels, biofuels are gaining prominence among shipping companies and cargo owners as alternatives to reduce GHG emissions. In this context, the GHG reduction effects of biofuels have been proven through various research and demonstration studies. As can be seen in the Figure 8-1, compared to other alternative fuels (especially carbon-free fuels like ammonia or hydrogen), biofuels have a higher level of technological maturity and relatively fewer issues to be resolved.

[1] Considers onboard fuel supply and storage, fuel conversion and emissions control systems

[2] Considers fuel toxicity, flammability and explosiveness

[3] Includes regulatory framework supporting onboard regulatory aspects, and market mechanisms supporting adoption

|Figure 8-1| Various alternative fuel options and their characteristics in the shipping sector towards net zero[21]

In terms of sustainability, this study also confirmed through a case study that an imaginary ship with a lower CII rating could improve its CII rating by increasing the blend ratio of biofuel. Notably, it was observed that using biofuel exclusively could upgrade a ship to an 'A' rating. The critical point is that fuels with a lower GHG carbon intensity from a life-cycle perspective have a greater effect on regulatory improvement. Although biofuels have a relatively lower GHG reduction effect than carbon-free fuels, such as ammonia or hydrogen, it is anticipated that biofuels or biofuel blends could be a short-term solution to meet regulatory requirements.

However, despite the confirmed sustainability and GHG reduction effects of biofuels that can be applied to ships, the absence of fuel quality standards for these biofuels means that reliance on traditional fuel quality criteria is necessary. Moreover, long-term use may lead to issues such as oxidative stability, microbial occurrence and growth, and compatibility with the component materials, necessitating the measures outlined in this report.

Furthermore, although the price of biofuels is expected to remain relatively stable in the future, production limitations owing to the finite amount of raw materials and potential price uncertainties arising from competition with other industries and modes of transportation are foreseeable. In other words, the availability of biofuels for ship fuel can vary depending on the sustainability of the raw materials and the demand for biomass in other sectors (such as the power generation industry, and terrestrial and aviation transportation), which, in turn, can affect both demand and price. Therefore, it is important to be aware of these factors.

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