METHANOL AS A MARINE FUEL

NOVEMBER 2023

PROVIDING THE BEST SERVICES,
CREATING A BETTER WORLD

KR KOREAN REGISTER


KOREAN REGISTER

Table of Contents

Executive Summary

Accelerating climate change has brought about huge changes in the maritime industry. This report aims to describe the characteristics of methanol as a next-generation alternative fuel for ships and deliver key differences between the fuel and other fuels through comparisons of characteristics.

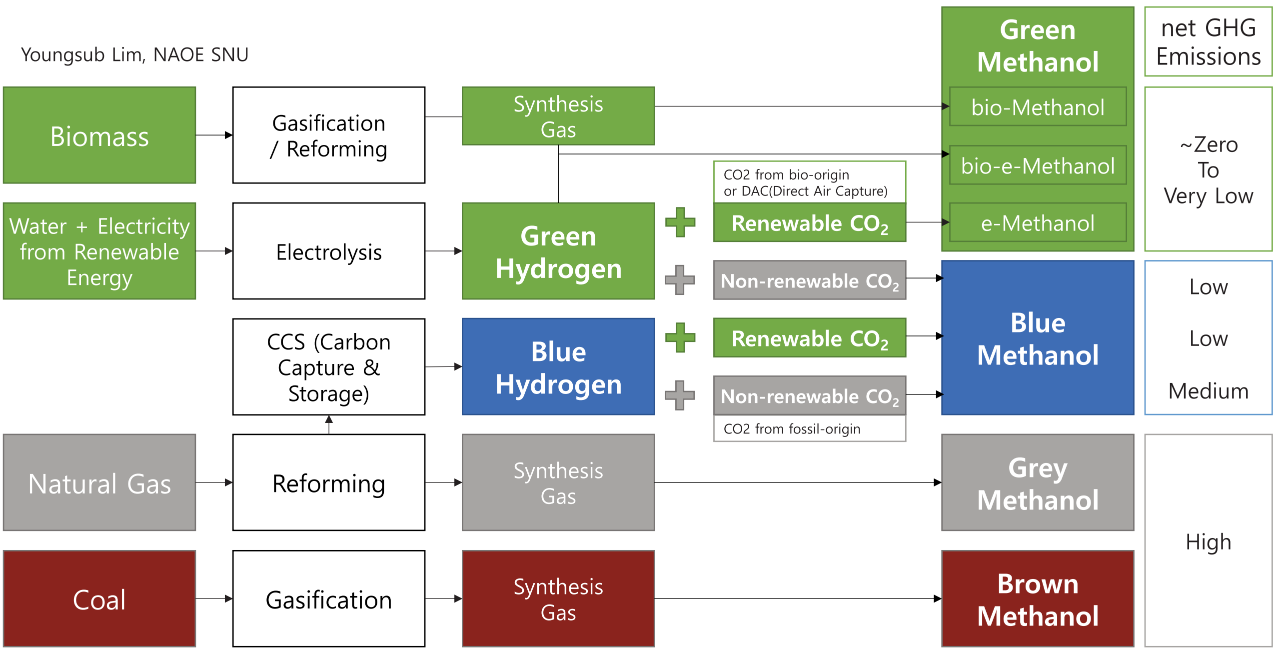
Chapter 1 introduces the background to climate change, regulations of greenhouse gas (GHG) emissions from ships, and furthermore, the growing interest in methanol. Especially, there would be accelerated changes due to the following issues discussed at the 80th MEPC meeting in July 2023.

- The final target should be revised upward: The achievement of net zero emissions around 2050. The rates of utilizing zero GHG technologies, fuels, and energy sources should be achieved at least 5% by 2030.
- GHG emissions should be assessed: Existing indices focus on calculating CO_2 emissions only, but the other GHGs having large global warming potential (GWP) should be included.
- Reduction of the total annual GHG emissions from international shipping by at least 20%, striving for 30%, by 2030, compared to 2008
- Reduction of the total annual GHG emissions from international shipping by at least 70%, striving for 80%, by 2040, compared to 2008.
- Total Well-to-Wake (WtW) GHG emissions intensity should be evaluated from the perspective of Life Cycle Assessment (LCA): The problems that existing indices only consider tank-to-wake (TtW) GHG emissions but not well-to-tank (WtT) emissions, should be addressed.
- Approval of interim guidelines for the use of biofuels (MEPC 376(80)): Provisional approval to allow biofuel emission reductions to be recognized only in the case of reducing more than 65% of the WtW GHG emissions intensity of fossil fuels. For reference, the standard for e-fuels has not yet been clarified, but it is likely to be 70% considering discussions on FuelEU Maritime, etc.
- Review on onboard CO_2 capture technologies in future.

The main reason for the current attention to methanol as a marine fuel is the possibility of producing green methanol with low or near-zero GHG emissions, such as bio-methanol or e-methanol. Although it is impossible to avoid CO_2 emissions from bio-methanol or e-methanol in the combustion stage, it is possible to lead to zero or very low CO_2 emissions by subtracting the amount of CO_2 absorbed by living organisms in the production stage. Additionally, as methanol is a liquid fuel rather than a fuel with a form of gas at atmospheric temperature, it has the great advantage of being able to utilize existing liquid-based infrastructure without major modifications. Furthermore, the commercialization level of methanol-fueled engines is high and applicable for immediate use, and it is possible to gradually achieve GHG emission targets by adjusting the use of conventional fuels and green methanol.

Chapter 2 handles the key features of methanol. Compared to conventional heavy fuel oil, methanol has low GHG and air pollutant emissions. Compared to hydrogen and ammonia, it has a better energy density, and is facile to utilize in commercial engines due to its good combustion characteristics. However, methanol is a corrosivity liquid, and a toxic substance that can cause serious damage to human health through oral ingestion, respiratory inhalation, and skin exposure.

Like hydrogen, methanol can be classified by color according to its production process (Figure ES-1). Green methanol, which has near-zero GHG emissions, can be distinguished into two types. The first is bio-methanol, which is produced from biomass that has absorbed CO_2. The second is e-methanol, which is produced by reacting green hydrogen obtained by electrolyzing water with electricity from renewable energy, with renewable CO_2 obtained from direct air capture (DAC), or bio-based CO_2. It should be noted that even if green hydrogen is utilized, methanol produced by synthesizing non-renewable CO_2 captured from fossil fuels could technically become blue methanol, since non-renewable CO_2 does not have GHG reduction effects from the LCA perspective.



|Figure ES-1| Color classification based on methanol production pathways

As for bio-methanol, assessing and reflecting of the impacts of land use change (LUC) have become an even more important issue. This is because it has long been pointed out that biofuel production has adverse effects such as reducing the cultivation of food crops and damaging rainforests. In terms of e-fuel, since the WtW GHG emissions can greatly vary due to the diversity of raw materials and production processes, it is important to assess this. FuelEU Maritime currently suggests a reduction of more than 70% of the baseline GHG emissions from fossil fuels (94 g_{CO2eq}/MJ in IMO) as a criterion for recognizing e-fuels. Table ES-1 indicates the WtW GHG emissions intensity for major fuels based on FuelEU Maritime and RED-II. The figures in this table are not yet confirmed, and may be changed in accordance with updated data in the future.

[Table ES-1] WtW GHG emissions intensity of marine fuels based on FuelEU Maritime.

Fuel Class	Pathway name	LHV (MJ/g)	WtT intensity (g co2eq /MJ)	Fuel Consumer Unit Class	TtW intensity (g co2eq /MJ)	WtW intensity (g co2eq /MJ)	WtW incl. ILUC[2] (gco2eq /MJ)	Source
Fossil	HFO (ISO 8217 Grades RME to RMK)	0.0405	13.5	All ICEs	78.2	91.7	-	FuelEU Maritime (EU, 2023)
	LFO (ISO 8217 Grades RMA to RMD)	0.041	13.2		78.2	91.4	-	
	MDO/MGO (ISO 8217 DMX to DMB)	0.0427	14.4		76.4	90.8[1]	-	
	LNG (Liquified Natural Gas)	0.0491	18.5	LNG Otto (DFMS)	70.7	89.2	-	
				LNG Otto (DFSS)	64.4	82.9	-	
				LNG Diesel (DFSS)	57.6	76.1	-	
	LPG (Liquified Petroleum Gas)[3]	0.046	7.8	ICE (Butane)	65.9	73.7	-	
				ICE (Propane)	65.2	73.0	-	
	H2 (from natural gas)[3]	0.12	132.0	ICE/Fuel Cells	0.0	132.0	-	
	NH3 (from natural gas)[3]	0.0186	121.0	ICE/Fuel Cells	0.0	121.0	-	
	Methanol (from natural gas)[3]	0.0199	31.3	ICE	69.1	100.4	-	
Biodiesel[3]	Crop biodiesel	0.0372	-61.7 to -0.9	All ICEs	76.6	44.7-50.1	56.7-62.1	
	Oil crop biodiesel					51.6-75.7	106.6-130.7	
	Waste cooking oil biodiesel					14.9	-	
	Animal fats from rendering biodiesel					20.8	-	
	Fischer-Tropsch diesel	0.044	-54.2 to -47.7		64.4	11.7-18.2	-	
Bio-methanol[3]	Waste wood methanol in free-standing plant	0.02	-55.3	All ICEs	68.8	10.4	-	
	Farmed wood methanol in free-standing plant		-52.6			13.5	-	
	Methanol from black-liquor gasification		-58.4			16.2	-	
Renewable Fuels of Non-Biological Origin (RFNBO) - (e-fuels)	e-diesel	0.0427	-48.2 이하	ICE	76.4	28.2 이하 (Based on 70% reduction)[4]	-	RED II (EU, 2018) / FuelEU Maritime (EU, 2023)
	e-methanol	0.0199	-40.9 이하	ICE	69.1		-	
	e-LNG	0.0491	-42.5 이하	LNG Otto (DFMS)	70.7		-	
			-36.2 이하	LNG Otto (DFSS)	64.4		-	
			-29.4 이하	LNG Diesel (DFSS)	57.6		-	
	e-H2	0.12	28.2 이하	ICE/Fuel Cells	0.0		-	
	e-NH3	0.0186	28.2 이하	ICE/Fuel Cells	0.0		-	

LHV: lower heating value; ICE: internal combustion engine; DFMS: dual fuel medium speed; DFSS: dual fuel slow speed; OPS: On-shore power supply; ILUC: Indirect land use change.

1) Current IMO fossil fuel WtW GHG intensity baseline of 94 g_{CO2eq}/MJ are not the same as the FuelEU Maritime (91.2 g_{CO2eq}/MJ).
2) The estimated result of WtW emissions intensity of biofuels when emissions due to indirect land use change (ILUC) are included
3) Impact of GHGs other than CO_2 emitted during combustion (CH4, N_2O) is not currently included, but may be revised later.
4) Based on RED II, the qualification criteria for e-fuel and bio-fuel are 70% and 65% reduction to fossil fuel WtW GHG emissions intensity.

Chapter 3 provides guidance on the regulations to be applied when using methanol as a fuel. The IMO has approved IMO MSC.1/Circular.1621 “Interim Guidelines for the safety of ships using methyl/ethyl alcohol as fuel” by extending and revising the IGF Code (International Code of Safety for Ships using Gases or other Low-flashpoint Fuels), which was applied to existing LNG vessels, for methanol- or ethanol-fueled ships. Currently methanol-fueled ships follow these interim guidelines.

In South Korea, in accordance with “Act on the Promotion of Development and Distribution of Environmentally-Friendly Vessels (Environmentally -friendly Ship Act),” ships using environmentally -friendly energy as fuels are recognized as eco-friendly ships; the Joint Ordinance "Rules on Standards and Certification of Environmentally Friendly Ships" stipulates methanol as an environmentally friendly energy. The Korean Register of Shipping (KR) has added “Appendix 5: Requirement for Ships Using Methyl/Ethyl Alcohol as Fuel” to the appendix of the KR “Rules for Ships Using Low-flashpoint Fuels” that was previously applied to LNG ship, so methanol-fueled ships are subject to the rule.

Chapter 4 introduces the current status of methanol engines, fuel tanks, and fuel propulsion systems. Several engine developers have developed or are in the process of developing dual-fuel propulsion engines fueled by methanol.

Since methanol is a liquid at atmospheric temperature, it has the advantage of being able to be utilized based on existing liquid fuel storage tank technology without the need to consider low-temperature liquid storage facilities and large boil-off gas treatment systems. Although the energy density of methanol is lower than that of LNG, it does not require additional spaces such as low-temperature insulation. Thus, the relative size of cargo handling system for methanol is similar to for LNG, even after considering cofferdam. This is estimated to be approximately half the cargo handling system size of liquefied ammonia and 30% of that of liquefied hydrogen.

When converting to methanol propulsion systems, a reduction in cargo capacity of approximately 1.5-4.0% is expected due to space conversion. To reduce the loss, it is necessary to prepare the structural elements and systems for methanol conversion. According to Clarksons, 43 methanol-fueled vessels were ordered in 2022, with 22 methanol-ready vessels also on order.

Chapter 5 deals with the risk factors of methanol. Methanol has a lower viscosity than conventional heavy fuel oil, which poses a risk of higher leakage frequencies. Methanol is absorbed into the body by all routes of ingestion, inhalation, and skin contact, and is a toxic substance that can cause optic nerve disorders, hepatotoxicity, nephrotoxicity, central nervous system disorders, and reproductive dysfunctions. It is also corrosive and highly flammable, capable of exploding in a fire. A caution is required, as the exhaust gas from methanol combustion may also contain formaldehyde, which is a toxic substance.

To prevent accidents, methanol handling facilities should be isolated, storage containers should be grounded, and there should be spark and static electricity protection. Ventilation and exhaust facilities are required, and if direct contact is inevitable, protective equipment such as air-supplied respirators, safety glasses, and protective clothing are required. Methanol-powered ships should conduct a risk assessment to confirm the risks from fuel use, and the main considerations are as follows.

(1) Equipment for storing and supplying fuel: manifolds, valves, piping, tanks, pumps, compressors, etc.
(2) Control equipment: pressure and temperature controllers, flow regulators, control panels, etc.
(3) Equipment for safety measures such as detection and alarm: leak detectors, fire detectors, etc.
(4) Fuel vent and treatment equipment: fuel vent pipes, masts and valves, overflow tanks, etc.
(5) Fire extinguishing system: water sprayers, water curtains, fire dampers, etc.
(6) Purging and inerting facilities: purging, nitrogen storage/supply devices for inerting, etc.
(7) Storage structure facilities: fuel storage hold space, tank connection area, fuel tank, etc.

Chapter 6 summarizes methanol production, economic feasibility, and bunkering. Methanol is a raw material for various chemical products such as paints, plastics, and building materials, and is widely produced and distributed around the world, and its market is expected to expand in the future due to the higher demand for alternative fuels. Bio-methanol currently achieves a high technology readiness level of TRL 8-9, but the capacity of commercial mass production is not yet sufficient. As for e-methanol, large-scale water electrolysis reactors are not available yet, and a large amount of renewable energy-based electricity is required for green hydrogen production, leading to high production costs.

The unit cost of gray methanol produced from natural gas is currently estimated to be around $20/GJ, that of bio-methanol is approximately $30/GJ, and that of e-methanol is around $66/GJ, indicating that bio-methanol and e-methanol are significantly higher than gray methanol. As for bio-methanol, it is highly influenced by the price of biomass, which is the base material, and is expected to reach $23/GJ in the future if the base material cost is reduced and the technology is sufficiently matured. E-methanol is greatly affected by the costs of green hydrogen, renewable energy electricity, and carbon dioxide supply. Particularly, as the cost of electricity required for water electrolysis accounts for a large proportion, it is necessary to reduce the renewable energy cost. Additionally, as Direct Air Capture (DAC) technology, which directly captures CO_2 from the air, has a low technology readiness level, its unit cost is very high. If technology readiness becomes sufficiently high, such as a high readiness of water electrolysis technology, and a lower price of renewable energy, it is expected that the unit price of e-methanol can reach $30/GJ.

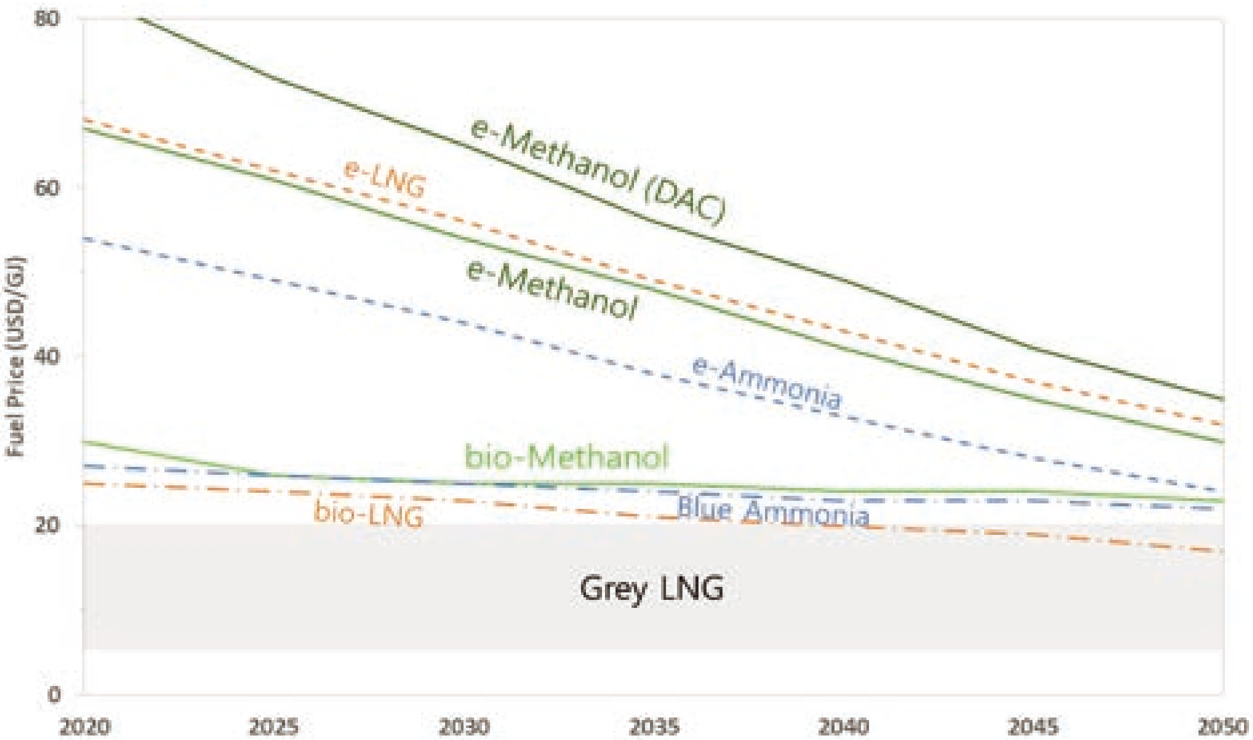
As the methanol bunkering system is similar to the existing liquid fuel bunkering system, it seems relatively easy to convert and build infrastructure compared to other low-flahspoint fuels. Methanol bunkering has already taken place in Belgium, the United States, and South Korea, and there will be more available ports for bunkering in the future. Technical documentation and guidelines for bunkering are required for safety reasons, and related work is in progress.

Chapter 7 concludes with the outlook for methanol as a marine fuel, while comparing it to LNG, hydrogen, and ammonia.

Compared to LNG, since gray methanol has higher WtW GHG emissions intensity (100.4 g_{CO2eq}/MJ), it is meaningless to consider it as an alternative fuel; therefore, it is more appropriate to make a comparison while focusing on bio-methanol or e-methanol. Bio-methanol has low WtW GHG emissions intensity of approximately 10.4-16.2 g_{CO2eq}/MJ; e-methanol may greatly vary in the intensity depending on the production process, but ideally, production from green hydrogen and renewable CO_2 can make it possible to be closer to net-zero emissions. Bio-methanol and e-methanol are currently priced higher than gray methanol and will require stabilization of biomass raw material prices, optimization of processes, maturation of CO_2 capture process prices and water electrolysis devices, and lower prices for renewable energy. Bio-LNG is evaluated to have a production cost that is more than twice as high as gray LNG, but it is estimated that it can be produced at a lower cost than bio-methanol and e-methanol; therefore, it is expected to be in demand for a considerable period of time. The LNG infrastructure is currently dominant, but considering the nature of methanol as a liquid fuel, it seems to be not difficult to expand the infrastructure if there is demand. The required cargo handling space is similar, and the engine technology readiness is also high.

Compared to hydrogen, gray hydrogen has a higher WtW GHG emissions intensity of 132 g_{CO2eq}/MJ, so it cannot become an alternative fuel, and it is appropriate to focus on blue or green hydrogen. Ideal green hydrogen would have near-zero GHG emissions, but the technology readiness of fuel cells and engines that can use hydrogen, is low, and large-scale production and bunkering facilities are insufficient; thus, the overall supply chain and infrastructure will take time to be built. The required space of cargo handling system is estimated to be more than three times that of methanol. Since the current unit cost of green hydrogen is very high, but that of blue hydrogen is relatively low, it is expected that a strategy to gradually reduce GHG emissions can be adopted by utilizing blue hydrogen to produce alternative fuels during the transition to green fuels in the long term.

Compared to ammonia, as gray ammonia has a higher WtW GHG emissions intensity of 121 g_{CO2eq}/MJ than that of fossil fuels, it is meaningless to consider it as an alternative fuel, and it is appropriate to focus on blue or green ammonia. Ideal green ammonia would have near-zero GHG emissions, but the GHG emissions of N_2O, which is known to be generated during ammonia combustion, have not been completely evaluated, which should be considered. As ammonia is highly toxic in water and toxic to humans, it is also necessary to consider the results of environmental assessments. As ammonia has been utilized as a fertilizer for a long time, it has a larger supply chain than methanol around the world, which is an advantage in terms of scale. However, the transportation conditions are -34°C at atmospheric pressure, which requires additional insulation and boil-off gas treatment systems compared to methanol, and resultantly, the required cargo handling space is estimated to be approximately twice that of methanol. As ammonia engines are still under development, it is necessary to confirm results regarding concerns about potential problems such as an ammonia slip. The cost of gray ammonia is lower than that of methanol, but it is estimated that the cost of e-ammonia is located halfway between that of bio-methanol and that of e-methanol. As the cost of e-ammonia is determined by the high cost of electricity required to produce green hydrogen and the energy consumption of the ammonia conversion process, it is expected to compete with green methanol as the technology matures in the future.



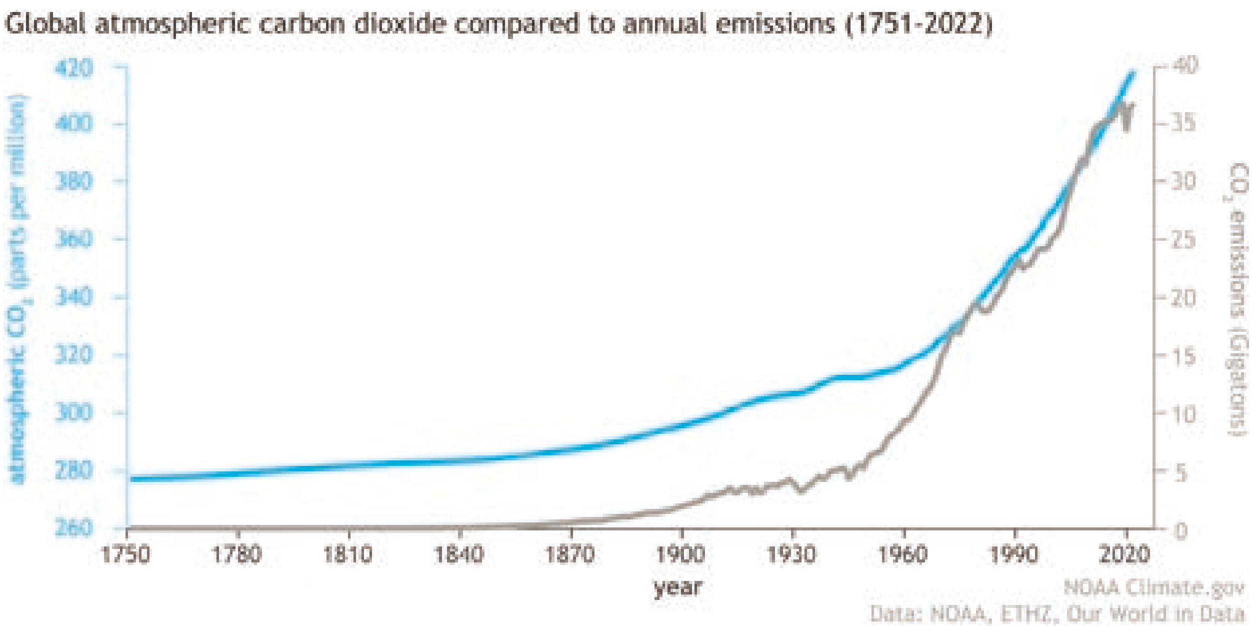
|Figure ES-2| Fuel price forecast for bio-/e-LNG, blue/e-ammonia, and bio-/e-methanol [64, 93-95, 113].

01 Background

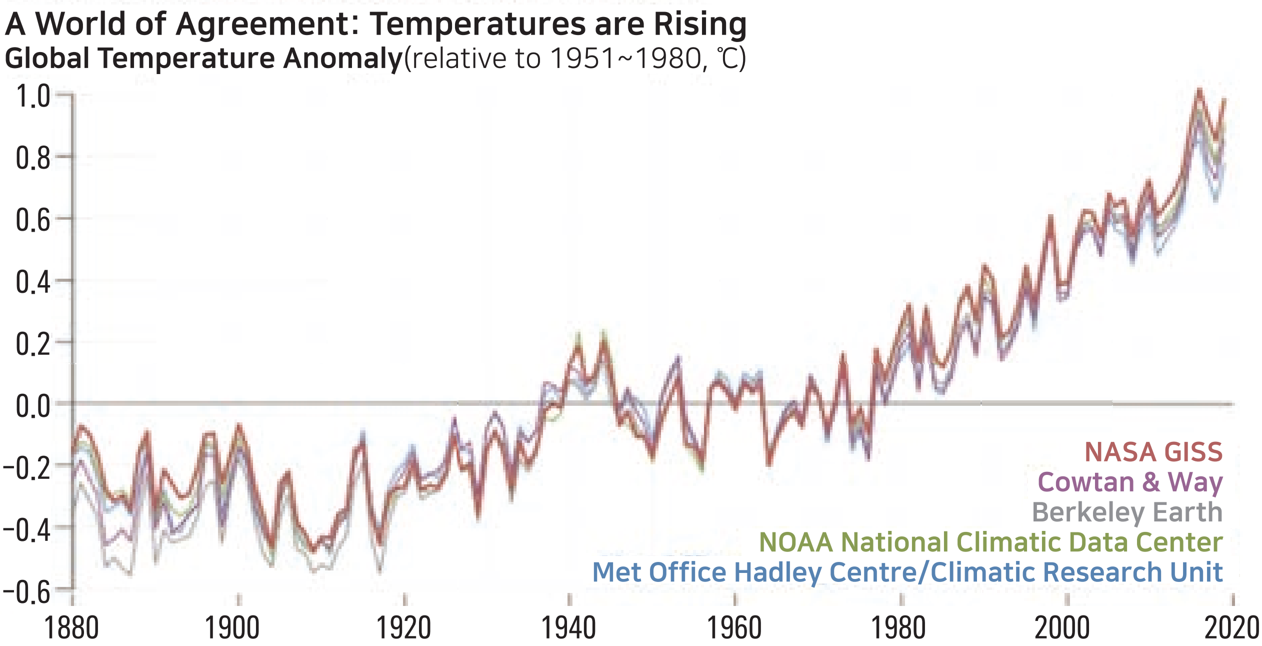
1.1. Climate Change and the Need to Reduce Greenhouse Gases

Since the Industrial Revolution, the atmospheric concentration of carbon dioxide (CO_2), a major greenhouse gas (GHG), has been rising steadily with explosive economic growth. In the last half-century, the rate of increase has accelerated dramatically, with the atmospheric CO_2 concentration already exceeding 400 parts per million (ppm) (Figure 1-1) [1]. Considering that the highest atmospheric CO_2 concentration in the last 800,000 years was around 300 ppm, the current atmospheric CO_2 concentration is the highest in history. Alongside the increase in atmospheric CO_2 concentration, the average temperature of the Earth has gradually risen, leading to global warming (Figure 1-2) [2].

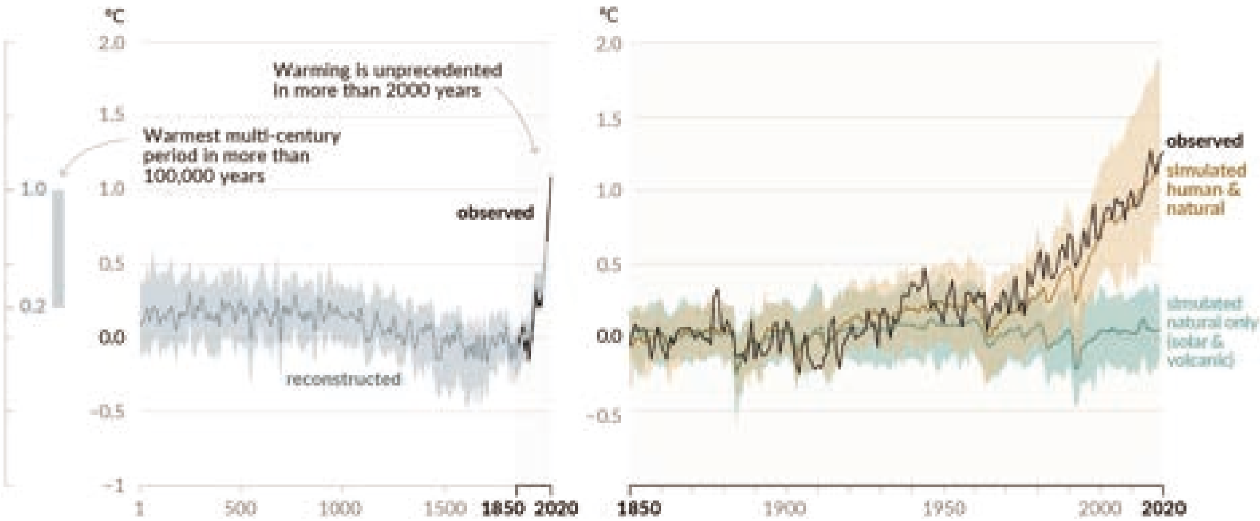
In the past, there was a view that the increase in CO_2 concentration was part of the natural cycle, but over time, there has been increasing support for a view on anthropogenic influence. The recently released sixth report of the Intergovernmental Panel on Climate Change (IPCC) affirms that humans are responsible for the cause of global warming (Figure 1-3) [3]. Due to the worsening climate change problem, global warming mitigation policies and environmental regulations have become goals that the world must achieve together. In the recently held 27th Conference of the Parties (COP27) to the United Nations Framework Convention on Climate Change (UNFCCC), it was agreed to establish a fund to compensate countries that have sustained damage due to the climate change problem [4].



|Figure 1-1| Anthropogenic CO_2 emissions (gray line) and atmospheric CO_2 concentration (blue line) [1]



|Figure 1-2| Temperature change (℃) from 1880 to 2020 relative to the average temperature in 1951-1980[2]



|Figure 1-3| Surface temperature changes reconstructed from paleoclimate records (gray solid line, years 1-2000) and direct observations (black solid line, 1850-2020) [3]

The Paris Agreement, adopted at the COP21 in 2015, includes a global long-term goal to limit the increase in the global average temperature to 2℃ or less compared to pre-industrial levels, striving not to exceed 1.5℃ if possible. All 195 Parties have joined the agreement, and each participating country has submitted a Nationally Determined Contribution (NDC) and pledged to implement it. The

2030 NDCs are interim targets targeted to be achieved by 2030, aiming at achieving the ultimate goal of carbon neutrality in 2050. The 2030 NDCs of major countries (2050 Commission on Carbon Neutrality and Green Growth, 2021) are shown in Table 1-1.

[Table 1-1] Summary of the 2030 NDCs of major countries

Country	2030 NDC (After Declaration of Carbon Neutrality)
Republic of Korea	40% reduction compared to 2018
EU	At least 55% reduction compared to 1990
United Kingdom	68% reduction compared to 1990
United States	50-52% reduction compared to 2005
Canada	40-45% reduction compared to 2005
Japan	46% reduction compared to 2013

Under the Paris Agreement, Parties have established sector-specific GHG reduction targets for each country. However, international shipping is not included as it falls outside the territorial waters of any specific Party. According to the International Maritime Organization (IMO) under the United Nations (UN), CO_2 emissions from the shipping sector in 2018 accounted for approximately 2.89% (1,056 million tonnes CO_2) of global CO_2 emissions, and about 1,076 million tonnes CO_2-eq in terms of GHG (IMO, 2021b). Based on the 2018 GHG emissions by country in Table 1-2, these emissions from the shipping sector rank eighth highest globally. The IMO has been actively working to reduce international shipping-related GHG emissions. Additionally, countries such as the European Union (EU) and the United States have proposed regulations and legislations to address shipping-related GHG emissions. Section 1.2 identifies trends in international shipping-related GHG emission regulations, and Section 1.3 introduces the background of methanol's emergence as an alternative marine fuel.

[Table 1-2] GHG emissions by country in 2018

Country	GHG emissions (million tonnes CO_2-eq)	Percentage
Global	54066.3	100.0%
China	12387.1	22.9%
USA	6272.4	11.6%
India	3783.8	7.0%
Russia	2324.1	4.3%
Brazil	2123.8	3.9%
Indonesia	2087.1	3.9%
Japan	1181.0	2.2%
Iran	969.3	1.8%
Mexico	863.5	1.6%
Canada	833.1	1.5%
Germany	827.3	1.5%
Saudi Arabia	763.7	1.4%
South Korea	714.2	1.3%

1.2. Trends in Environment Regulations for International Shipping

- Trends of IMO GHG Regulation

Since the 2000s, the IMO has initiated various efforts to reduce international shipping-related GHG emissions, outlined as follows [5].

1) EEDI (Energy Efficiency Design Index) and SEEMP (Ship Energy Efficiency Management Plan)

In 2011, the IMO adopted amendments to Annex VI of the International Convention for the Prevention of Pollution from Ships (MARPOL), mandating measures to reduce the carbon intensity of international shipping. Carbon intensity is defined as carbon emissions per transport work, where a transport work is a tonne · mile, representing the amount of cargo transported multiplied by the transportation distance. EEDI and SEEMP were adopted as part of these measures and became effective on January 1, 2013. These measures constitute the first global mandatory GHG reduction schemes for the international industrial sector and have been driving energy efficiency improvements in ships globally for over a decade.

EEDI is a ship energy efficiency design index applied during the construction of new ships, defined as CO_2 emissions per transport work, i.e., the amount of CO_2 emitted when transporting one ton of cargo one nautical mile (nm) (gCO_2/tonne · nm), based on the documented specifications of the new ship. IMO regulations mandate that a ship's Attained EEDI must be less than or equal to the Required EEDI for that year, depending on the ship type. Phase 1 of EEDI, implemented in 2015, required a 10% reduction in carbon intensity for new ships. Phase 2, implemented in 2020, mandated a 20% reduction in carbon intensity for new ships. Initially set for implementation in 2025 with a 30% reduction target (Phase 3), its application began in 2022 for container ships, LNG carriers, general cargo ships, cruise ships, and gas carriers over 15,000 DWT. Reduction rates have also been strengthened for new container ships, with carbon intensity reductions ranging from 15% to up to 50% depending on the size of the ship.

SEEMP is a document outlining procedures and methods for establishing, implementing, monitoring, and evaluating a plan to improve ship energy efficiency. The template for developing a SEEMP consists of three parts:

- Part Ⅰ: Ship management plan to improve energy efficiency
- Part Ⅱ: Ship fuel oil consumption data collection plan
- Part Ⅲ: Ship operational carbon intensity plan

2) IMO DCS (Data Collection System)

Regulation of the existing ships requires that the energy efficiency of operating ships can be estimated, and this requires measures to obtain operational data from actual ships. In October 2016, at the 70th session of the IMO Marine Environment Protection Committee (MEPC), DCS regulations were adopted as a mandatory provision of MARPOL Annex VI. These DCS regulations are mandatory for the collection and reporting of fuel oil consumption data from ships over 5000 GT.

3) EEXI (Energy Efficiency Existing Ship Index) and CII (Carbon Intensity Indicator)

For the regulation of existing ships, the EEXI and CII was adopted in June 2021 under the Initial IMO GHG strategy, taking effect on January 1, 2023. EEXI applies to all existing ships over 400 GT on international voyages. Similar to EEDI, it represents the amount of CO_2 generated when transporting one ton of cargo one nautical mile (nm) based on the ship's specifications. The estimated Attained EEXI result must be less than or equal to the Required EEXI for that year.

CII similarly refers to the amount of CO_2 generated when transporting one ton of cargo one nm, based on actual operational data and fuel oil consumption via IMO DCS. CII is mandatory for ships over 5000 GT and the ship is given a rating from A to E, by comparing the Attained CII against the Required CII. For ships that receive a D rating for three consecutive years or E rating in a single year, a corrective action plan is required to be developed and approved.

4) IMO Greenhous Gas Report

The IMO initiated research on GHG in 1997 through the MEPC, resulting in IMO GHG Reports published in 2000, 2009, 2014, and 2020 [6]. The Fourth IMO GHG Report in 2020 provides an analysis summary of the GHG emissions inventory and carbon intensity for the shipping sector from 2012 to 2018. Among them, information on global CO_2 emissions and shipping-related CO_2 emissions is shown in Table 1-3 [7]. It can be observed that from 2012 to 2018, shipping-related CO_2 emissions increased from 962 million tonnes to 1,056 million tonnes, and the share of shipping in global CO_2 emissions increased from 2.76% in 2012 to 2.89% in 2018.

[Table 1-3] Comparison of global CO_2 emissions and shipping-related CO_2 emissions [7]

Year	Global anthropogenic CO_2 emissions (million tonnes)	Total shipping CO_2 (million tonnes)	Total shipping as a percentage of global
2012	34,793	962	2.76%
2013	34,959	957	2.74%
2014	35,225	964	2.74%
2015	35,239	991	2.81%
2016	35,380	1,026	2.90%
2017	35,810	1,064	2.97%
2018	36,573	1,056	2.89%

5) Initial IMO GHG Strategy

In 2018, the IMO's initial GHG strategy was adopted, outlining the goal of reducing annual GHG emissions from international shipping by over half by 2050 compared to 2008 levels, with efforts to phase out GHG emissions from shipping within this century. The strategy has three main objectives:

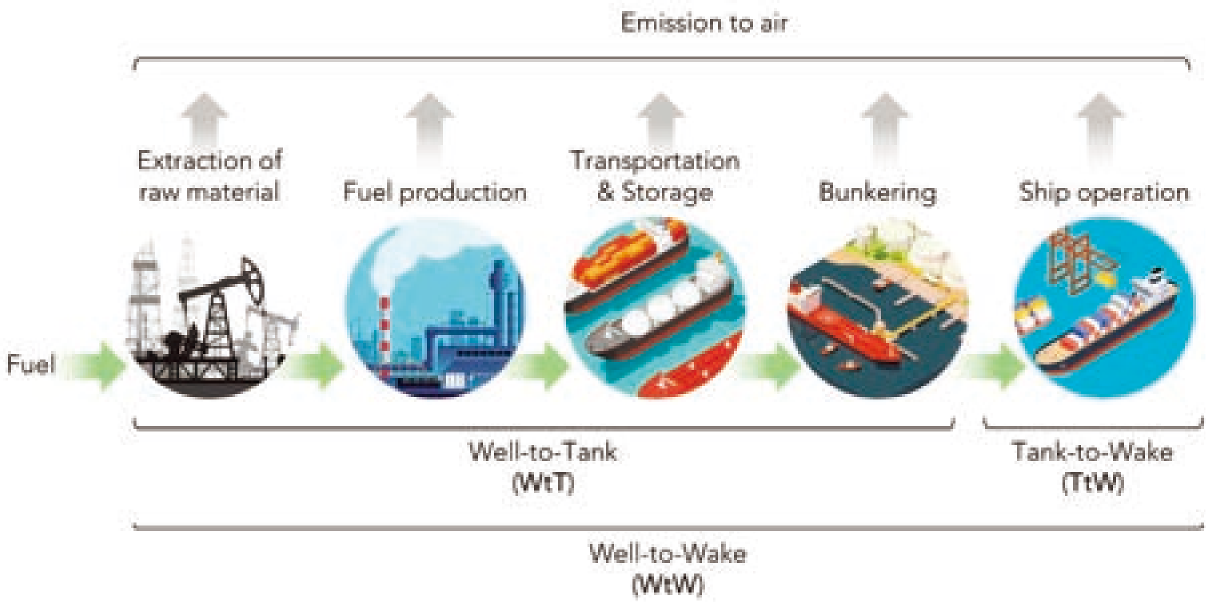
- Reduce the carbon intensity of ships through the implementation of additional phases of EEDI for new ships, with the percentage improvement for each phase determined by ship type as appropriate.
- Reduce the carbon intensity of international shipping, striving to reduce CO_2 emissions per transport work by at least 40% by 2030 compared to 2008 levels, with a target of a 70% reduction by 2050. (Subsequently amended and strengthened in the 2023 IMO GHG Strategy)
- Reduce GHG emissions from international shipping as soon as possible to achieve a reduction

of at least 50% in total annual GHG emissions in 2050 compared to 2008, and pursue efforts for phase-by-phase reduction as one of the CO_2 emission reduction pathways consistent with the Paris Agreement temperature targets.

6) 2023 IMO GHG Strategy

The IMO adopted the 2023 IMO Strategy on Reduction of GHG Emissions from Ships (the 2023 IMO GHG Strategy) at the 80th session of the MEPC in July 2023. This revised strategy includes a significantly strengthened goal, aiming to achieve net zero GHG emissions from international shipping by 2050. The key features of the 2023 IMO GHG Strategy are:

- It specifies that life-cycle GHG emissions should be considered, adopting life-cycle assessment (LCA) from production to use of marine fuels. This is a methodology that assesses well-to-wake (WtW) GHG emissions from the fuel production to the final use by ships, as shown in Figure 1-4 [8]. WtW is a concept that encompasses the well-to-tank (WtT) part (upstream emissions, ranging from the primary production to the transportation of fuel to bunker tanks) and the tank-to-wake (TtW) part (downstream emissions, ranging from the ship's fuel tanks to emissions).



|Figure 1-4| Concept of WtW life-cycle GHG assessment [8]

- The "Guidelines on lifecycle GHG intensity of marine fuels" (hereafter referred to as the LCA guidelines) is provided. The previous carbon intensity has been discussed and defined in terms of CO_2 emissions, but the LCA guidelines stipulate that GHG intensity should be considered including CO_2 and other GHGs also. In other words, the total amount of CO_2 equivalent GHGs emitted when transporting one ton of cargo one nautical mile (g_{CO2eq}/tonne · nm) should be assessed. This means that the CO_2 equivalent GHG emissions per transport work, including the impact of GHGs with high global warming potential such as methane and nitrous oxide, should be considered.

- Uptake of zero (or near-zero) GHG emission technologies, fuels and/or energy sources to represent at least 5%, striving for 10%, of the energy used by international shipping by 2030: Regulations for the use of onshore power supply, environmentally non-damaging biofuels, onboard carbon capture and storage (CCS), e-fuels, and blue fuels are expected to be finalized.
- Raising the final target to achieve net-zero emissions by or around, i.e., close to 2050: This is a significant increase from the initial IMO GHG Strategy, which sought a 50% reduction in GHG emissions by 2050.
- Mid-term indicative checkpoints to reach net-zero GHG emissions from international shipping: To reduce the GHG intensity from international shipping by at least 20% (striving for 30%) by 2030, and by at least 70% (striving for 80%) by 2040, compared to 2008.
- Approval of temporary guidelines for the use of bio-fuels in accordance with regulations 26, 27 and 28 of MARPOL Annex VI (DCS and CII): Until a comprehensive method for the calculation of WtW GHG emissions based on the LCA guidelines (resolution MEPC 376(80)) is developed, biofuels that have been certified by an international certification scheme, meeting its sustainability criteria, and that provide a WtW GHG emissions reduction of at least 65% compared to the WtW emissions of fossil fuel of $94g_{CO2eq}$/MJ (i.e. achieving an emissions intensity not exceeding $33g_{CO2eq}$/MJ) may be assigned a Cf equal to the value of the WtW GHG emissions of the fuel according to the certificate (expressed in g_{CO2eq}/MJ) multiplied by its lower calorific value (LCV, expressed in MJ/g) for the purpose of regulations 26, 27 and 28 of MARPOL Annex VI for the corresponding amount of fuels consumed by the ship. In any case the Cf value of a biofuel cannot be less than 0. For blends, the Cf value should be calculated on the weighted average of the Cf for the respective amount of fuled by energy. For biofuels that do not meet the sustainability criteria or do not meet the WtW emissions criteria above (at least 65% reduction), a Cf equal to the equivalent fossil fuel type should be assigned.
- Onboard CO_2 capture: It was agreed to review the submissions related to onboard CO_2 capture and, if possible, to review the related proposals in ISWG-GHG 16, which was to be held before MEPC 81, and consider for future directions.

Table 1-4 shows the future timetable for the 2028 IMO Strategy.

[Table 1-4] Future MEPC plan for the 2028 IMO Strategy

Target Date	MEPC	Description
Spring 2024	MEPC 81	Interim report on comprehensive impact assessment of the basket of candidate mid-term measures/finalization of basket of measures
Fall 2024	MEPC 82	Finalized report on comprehensive impact assessment of the basket of candidate mid-term measures
Spring 2025	MEPC 83	Review of the short-term measure to be completed by 1 January 2026
Fall 2025	-	Adoption of mid-term measures at the extraordinary MEPC
Spring 2026	MEPC 84	Review of the short-term measures (EEXI and CII) to be completed by 1 January 2026 and approval of measures
Fall 2026	MEPC 85	-
2027	-	Entry into force of measures 16 months after adopting the mentioned measures
Summer 2027	MEPC 86	Initiating the review of the 2023 IMO GHG Strategy
Spring 2028	MEPC 87	-
Fall 2028	MEPC 88	Finalization of the review of the 2023 IMO GHG Strategy with a goal of adopting the 2028 IMO Strategy on reduction of GHG emissions from ships

- Trends of IMO Nitrogen Oxides (NOx) and Sulfur Oxides (SOx) Regulation

The IMO imposed regulations to limit pollutants such as NOx and SOx, in gas emitted by ships. The contribution of shipping to the total global production of these two pollutants is in the range of 13-15% and 12-13%, respectively [6, 9]. For this reason, the IMO has applied several regulations within MARPOL Annex VI to reduce NOx and SOx emissions from shipping activities, which are described in Tables 1-5 and 1-6.

[Table 1-5] IMO's NOx regulations [6]. (ECA: Emission Control Area)

Tier	Ship construction date or After	Total weighted cycle emission limit, (g/kWh), n = Engine's rated speed (RPM)		
		n<130	n=130-1999	n≥2000
Tier Ⅰ	January 1, 2020	17.0	$45 \times n^{-0.2}$	9.8
Tier Ⅱ	January 1, 2011	14.4	$44 \times n^{-0.2}$	7.7
Tier Ⅲ (ECA)	January 1, 2016	3.4	$9 \times n^{-0.2}$	2.0

[Table 1-6] IMO's SOx regulations [6].

Outside an ECA (Emission Control Area)	Inside an ECA
4.50% prior to January 1, 2012 3.50% on and after January 1, 2012 0.50% on and after January 1, 2020	1.50% prior to July 1, 2010 1.00% on and after July 1, 2010 0.10% on and after January 1, 2015

- EU Regulatory Trends

1) Fit for 55

On July 14, 2021, the European Commission established the objective of reducing net GHG emissions by at least 55% by 2030 compared to 1990 levels and introduced the Fit for 55 package to achieve this target. The package encompasses several directives (EU ETS, CBAM, ReFuelEU Aviation, FuelEU Maritime, etc.) designed to align EU legislation with the 2030 goal. Among these, the FuelEU Maritime initiative stands out as a key component for decarbonizing the maritime sector.

2) FuelEU Maritime

The primary goal of the FuelEU Maritime initiative is to enhance the production and adoption of sustainable alternative fuels, thereby reducing GHG emissions from the maritime sector in accordance with the EU's Fit for 55 package objectives. In June 2022, the European Council endorsed the proposal, and in March 2023, the European Council and Parliament reached a provisional agreement on the FuelEU Maritime proposal.

The FuelEU Maritime regulation consists of two main parts. The first part regulates the GHG intensity of energy used by ships, imposing obligations on ships over 5,000 GT calling at European ports to decrease the GHG intensity of energy used on board. These reduction goals are set to increase progressively from 2025 to 2050 (refer to Table 1-7). The second part concerns onshore power supply (OPS), mandating that the power required by a ship while docked must be supplied through OPS unless other eco-friendly technologies are utilized.

[Table 1-7] GHG intensity reduction goal compared to 2020 according to the FuelEU Maritime

Year	GHG Intensity Reduction Goal
2025	2%
2030	6%
2035	14.5%
2040	31%
2045	62%
2050	80%

- U.S. Regulatory Trends

1) Clean Shipping Act of 2023

The U.S. Clean Shipping Act of 2023, introduced in June 2023, aims to safeguard the health and environment of port communities by reducing GHG emissions from the shipping industry. Applicable to all maritime transportation companies trading with the United States, this Act aligns with the 1.5℃ goal of the Paris Agreement, and the U.S. Environmental Protection Agency (EPA) will establish progressive carbon intensity standards to decrease GHG emissions by 2040. Key highlights include:

- Carbon intensity requirements for marine fuels: It is required to achieve a life-cycle GHG reduction of 20% beginning January 1, 2027; 45% beginning January 1, 2030; 80% beginning January 1, 2035; and 100% beginning January 1, 2040.
- In-port vessel requirements by 2030: By January 1, 2030, all ships berthed or moored in U.S. ports must achieve zero GHG emissions and air pollutant emissions.

2) International Maritime Pollution Accountability Act

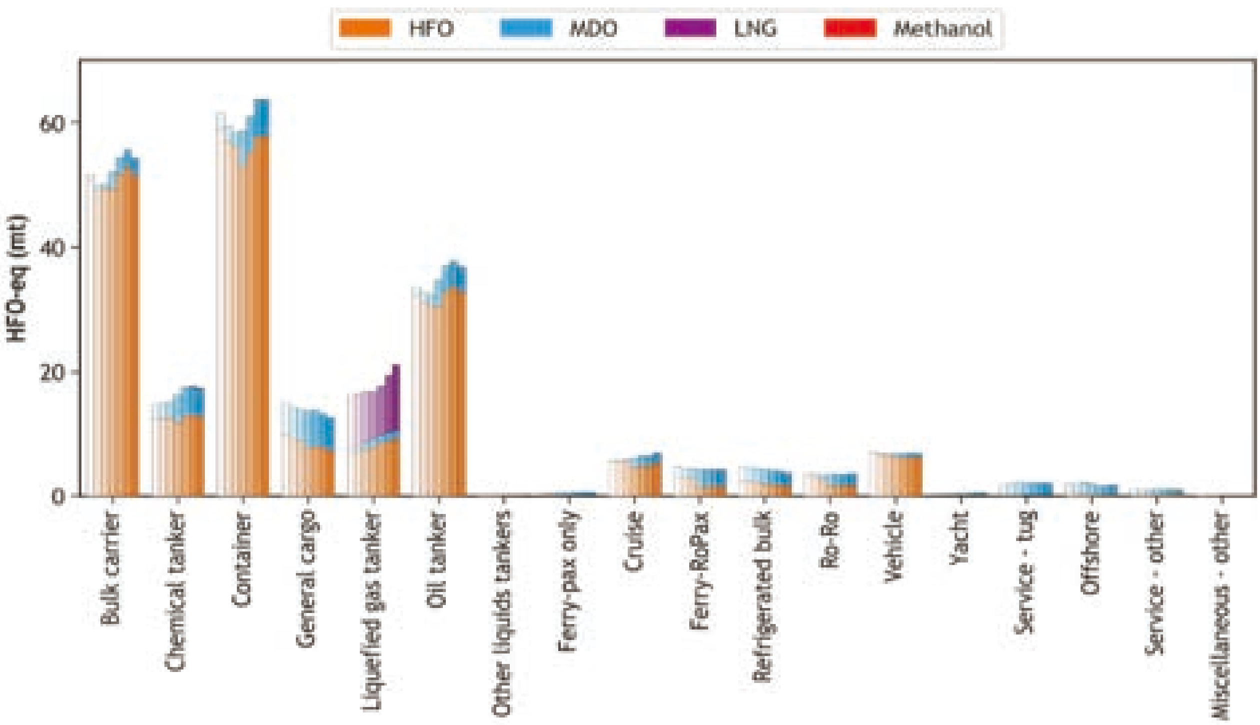
The International Maritime Pollution Accountability Act, co-introduced in June 2023 with the Clean Shipping Act of 2023, seeks to reduce emissions by imposing pollution levies on emissions from large ships unloading cargo at U.S. ports. Levies will be imposed on internationally voyaging vessels of 10,000 GT or more:

- Carbon emissions: \$150/ton CO_2
- Nitrogen oxide emissions: \$6.3/lb NOx
- Sulfur dioxide emissions: \$18/lb SO_2
- Particulate matter (PM2.5) emissions: \$38.9/lb PM2.5

1.3. Background on the Growing Interest in Methanol

- Environmental Issues with Conventional Marine Fuels

Since the Industrial Revolution, humanity has heavily relied on fossil fuels as a significant energy source. However, the use of fossil fuels containing carbon results in substantial GHG emissions. Figure 1-5 illustrates estimates of fuel consumption by ship type from 2012 to 2018, highlighting container ships, bulk carriers, and oil tankers as major contributors to GHG emissions in the international shipping sector. Notably, as of 2018, 79% of total fuel consumption by energy content was heavy fuel oil (HFO), indicating its continued dominance in international shipping [7]. LNG fuel produces fewer GHG emissions than conventional HFO, fossil-fuel-based LNG cannot be considered carbon-free in the long term, necessitating alternative fuels reducing GHG emissions in accordance with increasingly stringent IMO regulations.



|Figure 1-5| HFO-equivalent fuel consumption for international voyages by ship type [7]

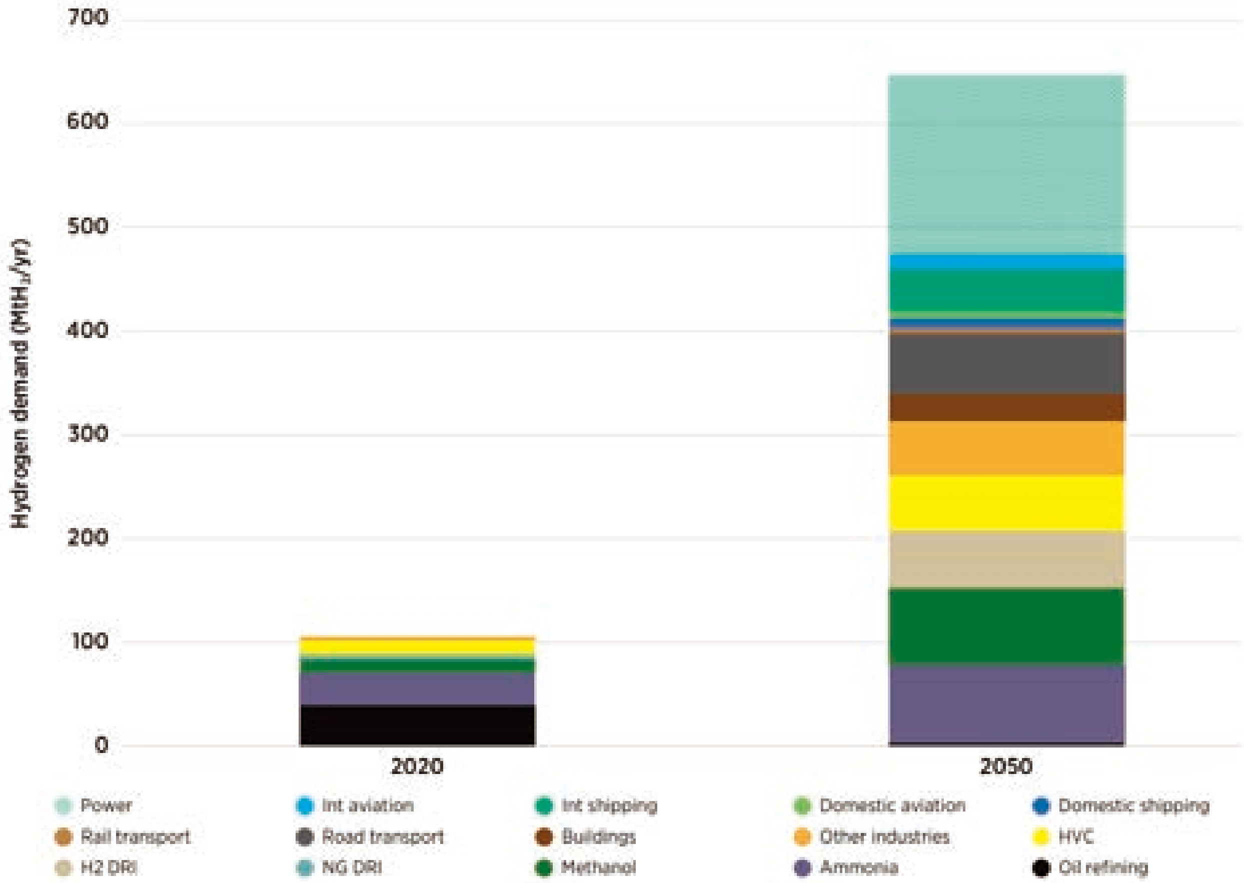
- Renewable Energy and PtX (Power-to-X)

Renewable energy as a substitute for fossil fuels has long attracted attention. Renewable energy refers to a renewable source of energy derived from solar, wind, tidal, wave, and geothermal sources, and its share of global power generation has been growing rapidly over the past decade [10-11]. Initially, the majority of renewable energy came from hydropower generation, but as conditions for efficient hydropower generation have diminished, renewable energy generation from wind and solar has steadily grown [10-11]. However, renewable energy sources such as wind and solar power have the intermittent nature as they are highly influenced by weather and seasonality, which can lead to the problem of inconsistent power supply and the problem of oversupply during hours of low power demand. To solve the oversupply problem, output can be curtailed, but since this means wasting energy, there is an active debate on how to convert the surplus power into other useful energy or materials. This is called power-to-X (PtX). PtX is a general term for various different methods in which surplus power in excess of the required load from highly volatile renewable energy generation can be stored or reconverted into other forms for use. There are several different types of PtX.

- Power-to-Power: Batteries / Compressed-air energy storage (CAES)
- Power-to-Mobility: Battery electric vehicles
- Power-to-Heat: Heat pumps
- Power-to-Fuel: Hydrogen by electrolysis (Green hydrogen)

- Green Hydrogen and e-Fuel

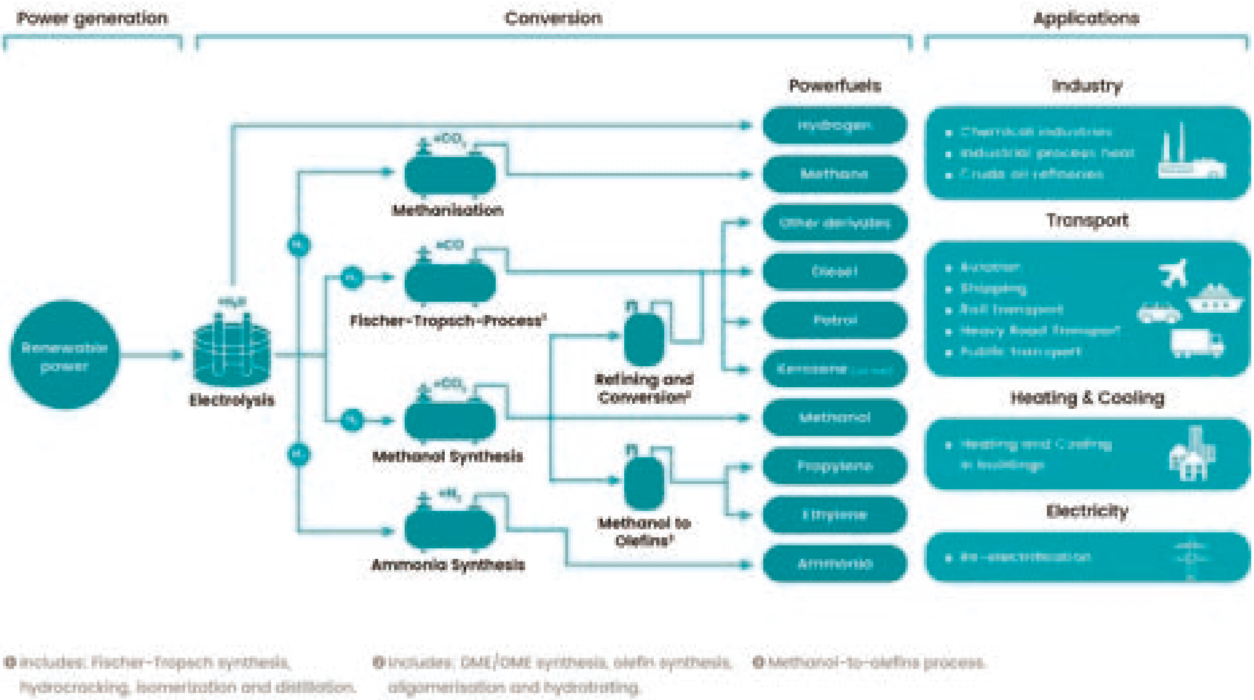
The power-to-fuel (PtF) method is a representative PtX method that converts surplus electricity into fuel, and in particular, green hydrogen utilizing renewable energy-based water electrolysis technology is gaining attention. One of the reasons is that hydrogen is highly versatile across the production and utilization stages and is used as a raw material for various chemical products. Currently, in the 1.5℃ scenario based on the Paris Agreement, the use of hydrogen is expected to contribute about 10% to carbon emission reduction [12-13]. Hydrogen is especially likely to be used in areas where it is difficult to store and use large amounts of electricity, and hydrogen demand is expected to grow rapidly from 2020 to 2050, with projected hydrogen demand in 2050 reaching more than 600 million tonnes per year (Figure 1-6).



Note: Hydrogen demand for 2020 excludes hydrogen as part of the mix of off-gases for steel production. DRI = direct reduced iron; HVC = high-value chemicals; Int = international; NG = natural gas.

|Figure 1-6| Hydrogen demand forecast by sector for 2020 and 2050 [12]

High-pressure compressed or liquefied hydrogen can be used for transportation and storage of hydrogen, but they both require large amounts of energy and cost for transportation because extremely high pressure of 350-700 bar is required for high-pressure compression and cryogenic temperature of -253℃ is require for liquefaction. Therefore, in areas that require large amounts of energy, such as shipping, it may be advantageous to synthesize fuels based on hydrogen as a raw material rather than using hydrogen directly [12-13]. E-fuel, which has been much discussed recently, is an abbreviation for electro-fuel and is a general term for fuels synthesized using green hydrogen obtained from renewable energy-based water electrolysis technology and carbon that is not based on fossil fuels, as raw materials. E-fuels are a type of synthetic fuels, but they are expected to contribute significantly to carbon neutrality. As shown in Figure 1-7, the types of e-fuels vary widely depending on the production method, and in the shipping sector, e-methanol and e-ammonia are gaining great attention as environmentally friendly marine fuels.



|Figure 1-7| Different e-fuel production pathways [14]

- Life Cycle Assessment (LCA) and Methanol as a Marine Alternative Fuel

Conventional research on marine fuel GHG emissions has mainly focused on assessing TtW emissions, i.e., GHG emissions resulting from combustion without considering the production process. However, when analyzing the overall impact on earth, WtT GHG emissions in the production process are also an important factor, and it is therefore important to assess WtW GHG emissions through LCA. The revised 2023 IMO GHG Strategy specifies this part and provides LCA guidelines.

From this perspective, it is not so much about what fuel is used, but how it is made. For example, in the case of gray methanol produced from conventional natural gas, the TtW GHG intensity from the combustion stage are 69.1 ($g_{CO2e}q$/MJ), which is around 10% lower than the 78.2 for HFO, but the WtW GHG intensity, including the emissions from the production stage, are 100.4, which is 9% higher than the 91.7 for HFO (Table 2-8). On the other hand, if bio-methanol is produced based on biomass or e-methanol is produced using green hydrogen and carbon dioxide captured from the atmosphere, ideally, the methanol can be a near-net zero GHG emissions fuels. Bio-methanol and e-methanol are also hydrocarbon-based fuels, meaning that they emit GHGs when burned. However, depending on the source of the CO_2 used as a raw material in the production stage, the CO_2 emitted after combustion can be subtracted from a life-cycle perspective. Therefore, if the net CO_2 emissions are found to be close to zero in the WtW assessment based on LCA, it can be recognized as an alternative renewable fuel. Furthermore, methanol has the advantages that most of the existing liquid fuel infrastructure can be used, and that carbon reduction can be gradually achieved by increasing e-methanol production as green hydrogen is commercialized. This is why methanol is attracting attention as an alternative marine fuel to respond to international shipping GHG regulations in the future.

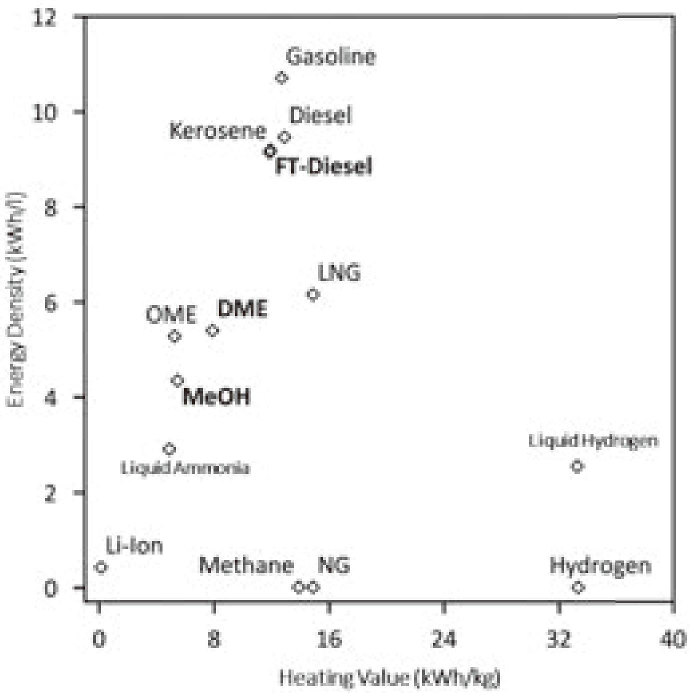
02

Properties of Methanol

2.1. Key Properties of Methanol

- Energy Density

Energy density is one of the key properties of a fuel and refers to the heating value per unit volume of fuel. The energy density of fuel, which affects the fuel tank size, is an important design factor, especially for ships having severe spatial constraints. Figure 2-1 illustrates the energy densities for various fuels. Methanol has a lower energy density than conventional fossil fuels such as gasoline and diesel, but has a higher energy density than ammonia and hydrogen, which have been mentioned as alternative fuels. Methanol has the advantage of being a liquid at standard temperature and pressure, making it much easier to handle than LNG and hydrogen, which require cryogenic temperatures to be transported as a liquid [16-17]. Table 2-1 shows information on the physical properties and combustion emissions for various marine fuels, and Table 2-2 shows the relative ratings of various fuel properties.



|Figure 2-1| Comparison of heating value and energy density of fuels [15]

(MeOH: Methanol, FT: Fischer-Tropsch, *Di-Methyl Ether at 10 bar, ** LNG at −160 ℃)

[Table 2-1] Information on physical properties and combustion emissions for various marine fuels [18]

Fuels	Chemical formula	Density at 15℃ (kg/m^3)	Cetane number	Octane number	Boiling point (℃)	Auto-ignition temperature in air (℃)	Flammability limits in air (vol%)	Combustion emissions in ICE			
								CO_2	SOx	NO_X	PM
LSHFO	C8-C25	975-1010	>20	—	>180	230	0.6-0.75	high	medium	high	medium
MDO	C10-C15	796-841	>35	—	>180	210	0.6-0.75	high	low	high	low
NG	CH_4	0.78	—	130	−162	540	5.0-15.0	medium	low	medium	low
PG	C_3H_8 C_4H_{10}	1.90	—	94-112	−42	450	2.1-9.5	medium	low	medium	low
Methanol	CH_3OH	792	<5	—	65	464	6.7-36.0	medium	low	medium	low
Ethanol	C_2H_5OH	789	5-15	—	78	365	3.3-19.0	medium	low	medium	low
DME	CH_3OCH_3	665	55-65	—	−25	350	3.4-27.0	medium	low	medium	low
Hydrogen	H_2	0.09	—	>130	−253	585	4.0-75.0	low	low	high	low
Ammonia	NH_3	0.73	—	120	−33	651	15.0-28.0	low	low	high	low
SVO	C14-C22	900-960	30-45	—	>180	424	0.6-7.5	high	low	high	low
FAME	C16-C18	860-900	45-55	—	>180	261	0.6-7.5	high	low	high	low
HVO	C15-C18	770-790	>70	—	>180	204	0.6-7.5	high	low	high	low
FT diesel	C15-C18	774-782	74-80	—	>180	204	0.6-7.5	high	low	high	low

LSHFO: Low Sulphur Heavy Fuel Oil, MDO: Marine Diesel Oil, NG: Natural Gas, PG: Petroleum Gas, DME: Di-Methyl Ether, SVO: Straight Vegetable Oil, FAME: Fatty Acid Methyl Esters, HVO: Hydrotreated Vegetable Oils, FT diesel: Fischer-Tropsch diesel, SOx: Sulphur Oxides, NOx: Nitrogen Oxides, PM: Particulate Matters

[Table 2-2] Relative ratings of different fuels by criteria [16]

Criteria	LNG	Methanol	HVO	Ammonia	Hydrogen	Fully electric
Energy density	4	4	5	3	2	1
Technological maturity	4	3	5	2	2	3
Local emissions	4	4	2	3	5	5
GHG emissions	2	2	4	5	5	5
Energy cost	5	3	2	1	1	Varies
Capital cost	4	4	5	4	1	5
Converter storage	3	4	5	4	1	1
Bunkering availability	4	3	1	2	1	2
Commercial readiness	5	4	3	2	1	Varies
Flammability	5	4	5	2	1	5
Toxicity	5	3	5	1	5	5
Regulations and guidelines	5	4	5	3	1	4
Global production capacity and locations	5	3	2	3	3	1

1: Poor - 5: Excellent.

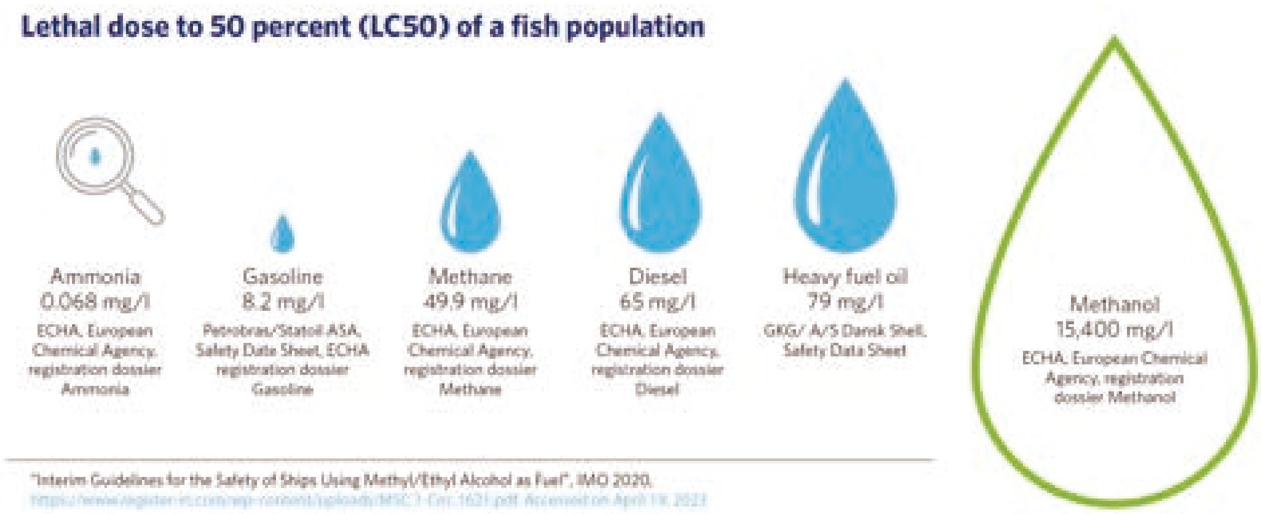
- Combustion Properties

Methanol is a highly flammable liquid alcohol fuel with a low flash point [6, 19]. It has a heating value of about 20 MJ/kg, which is lower than that of conventional marine fuels [6, 20], but produces fewer pollutants in exhaust gas [18]. Methanol has been used commercially as a fuel since the 1980s, but because alcohol has a low cetane number and a long ignition delay, methanol-blended fuels instead of pure methanol have been used for conventional compression ignition engines. When blended fuels are used, the percentage of methanol is typically between 5 and 30%, and additives are required to prevent phase separation [18, 22-23]. Recently, methanol engines are being developed as dual-fuel engines that can use methanol fuel based on a small amount of pilot fuels (see Chapter 4).

- Pollutant Emissions

Compared to conventional heavy fuel oil, methanol is known to reduce SOx by 99%, NOx by 80%, and GHG by up to 25% [24], so it is compliant with Emission Control Area (ECA) regulations [16]. Marine engine tests have shown that approximately 11.8 g/kWh of NOx is emitted when marine gas oil (MGO) is used as a fuel whereas NOx emissions are reduced by about 60-75% to 3-5 g/kWh when methanol is used [16, 25].

Methanol is water soluble, meaning that it dissolves quickly in water, unlike conventional heavy fuel oil, even if a direct spill of the fuel occurs. Most microorganisms have the ability to oxidize methanol to decompose it into carbon dioxide, and the examination of its impact on marine ecosystems reveals that it is about 200 times less toxic than conventional petroleum fuels (Figure 2-2) [26]. However, incomplete combustion of methanol can lead to the formation of formaldehyde, a toxic substance that can cause damage to human health. Table 2-1 shows an assessment of pollutant emissions for various marine fuels.



|Figure 2-2| Comparison of toxicity threshold (96hr LC50) for marine fish species bluegill [26].

- Risks

Methanol is a colorless, volatile, highly flammable, and toxic liquid. Since methanol is toxic to humans and it accumulates in the body through oral ingestion, respiratory inhalation, and skin exposure, methanol fueling systems and equipment should be installed in an enclosed area that blocks gas emissions. If methanol is absorbed into the human body, formaldehyde is produced, which can cause optic nerve damage, and its acute poisoning can cause respiratory damage. Methanol can also be absorbed through the skin, which means that dermal exposure should be avoided [24]. Fire and explosion risks should also be noted, as it is a flammable liquid that is susceptible to fire and explosion and has a relatively wide explosive limit range. Furthermore, methanol can corrode metals, so fuel storage tanks and fuel lines should be made of corrosion-resistant materials such as stainless steel. Methanol has properties to swell rubber, so careful material selection is required [24]. The risks of methanol are discussed in detail in Chapter 5.

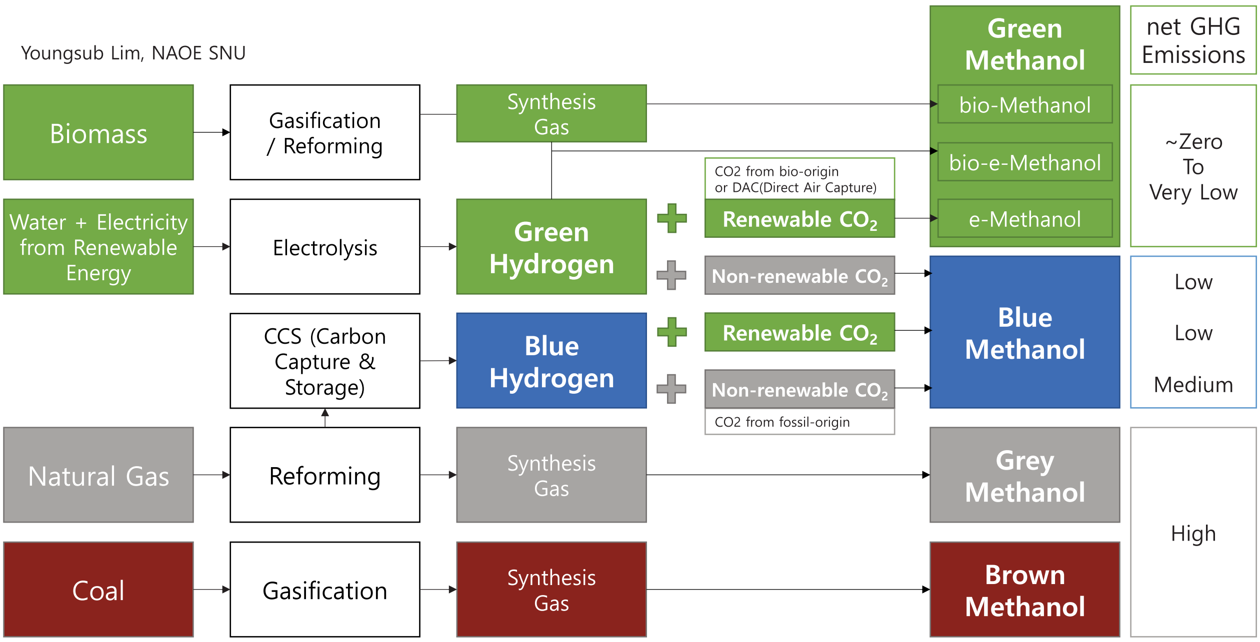
2.2. Color Classification Based on Methanol Production

In general, there are many different ways to produce methanol. The most common method is to reform natural gas or coal to produce synthesis gas (syngas), a mixture of CO and H_2, which then undergoes a synthesis process at high temperature and pressure under a catalyst to produce methanol. There is also a method that combines CO_2 and H_2 at high temperature and pressure to produce methanol (Table 2-3). This means that the GHG emissions in the production process of methanol can vary greatly depending on the raw materials and method of production.

[Table 2-3] Main reaction in methanol synthesis

From syngas	$CO+2H_2 \rightarrow CH_3OH$
From CO_2	$CO_2 + 3H_2 \rightarrow CH_3OH + H_2O$

To make it easier to classify methanol according to the level of its GHG emissions, a color classification can be applied similar to hydrogen. Currently, there is no international standard for the color classification of methanol, but by extending the concepts used to distinguish hydrogen, methanol can be largely classified as brown methanol, grey methanol, blue methanol, and green methanol, depending on the production pathway, as shown in Figure 2-3. Here, brown/gray methanol belongs to high carbon intensity methanol, while blue/green methanol belongs to low carbon intensity methanol.



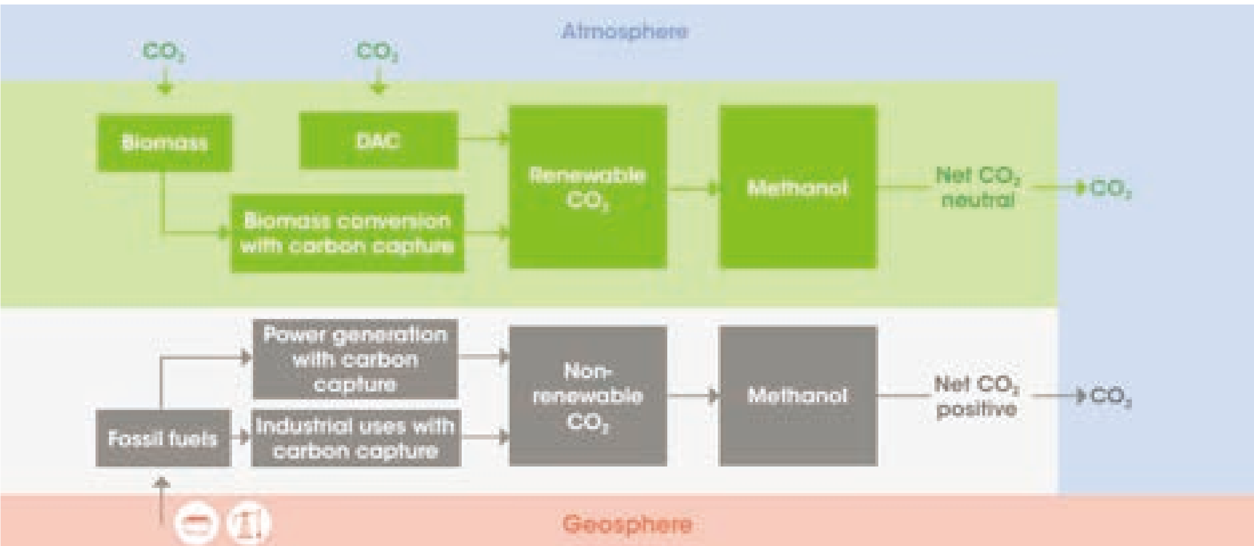
|Figure 2-3| Color classification based on different methanol production pathways

- Brown/Grey Methanol

Brown methanol refers to a method that produces methanol from syngas obtained by gasifying coal, i.e., brown hydrogen and carbon monoxide, and this method has the highest carbon intensity. Grey methanol refers to a method that produces methanol from grey hydrogen and CO obtained by reforming natural gas, and it emits less carbon than brown methanol, but still has high carbon emissions as its feedstocks include a fossil fuel. For methanol produced from natural gas, the WtW GHG emissions are about 10% higher than for HFO or MDO (see Table 2-8). Currently, about 98 million tonnes of methanol are produced annually, and since more than 90% of hydrogen is currently produced from fossil fuels [27], most of the methanol produced today is also brown/grey methanol, which is produced from fossil fuels [18, 28-29].

- Blue Methanol

Blue methanol refers to methanol whose feedstocks are partially produced from fossil fuels, but whose WtW GHG emissions are significantly lower than those of conventional grey methanol by GHG emission reduction technology, such as Carbon Capture, Utilization and Storage (CCUS) technology. Depending on how the feedstocks such as H2 and CO_2 are made, various cases can occur. For example, as shown in Figure 2-3, there are cases of producing blue methanol from (1) blue hydrogen and non-renewable CO_2, (2) blue hydrogen and renewable CO_2, and (3) green hydrogen and non-renewable CO_2. The renewable CO_2 means carbon dioxide obtained from CO_2-absorbed biomass or from direct air capture (DAC) utilizing renewable energy. In this case, the production process includes a process of reducing CO_2 in the atmosphere, so the CO_2 emissions in the combustion stage are offset, resulting in net-zero or net-neutral emissions or even net-negative emissions. Non-renewable CO_2, on the other hand, is the carbon dioxide emitted based on fossil fuels, which can eventually result in a net-positive emissions of CO_2 into the atmosphere. (Figure 2-4)



|Figure 2-4| Pathways of renewable CO_2 and non-renewable CO_2 [29]

1) Blue methanol produced from blue hydrogen and non-renewable CO_2

Blue hydrogen is produced by capturing and sequestering a portion of the CO_2 generated during the production of hydrogen from natural gas using CCUS technology. Since a significant amount of CO_2 is sequestered and not emitted during the production process of blue hydrogen, when it is combined with CO_2 to make methanol, blue methanol with reduced GHG emissions can be produced compared to brown/grey methanol, which emits GHG in both the production and combustion stages. However, if non-renewable CO_2 released from fossil fuels is used, all combustion products eventually contribute to atmospheric GHG emissions. In other words, this method has limitations to reducing WtW GHG emissions.

2) Blue methanol produced from blue hydrogen and renewable CO_2

Fuels based on biomass, such as photosynthesizing plants, can have negative values for GHG emissions in the production stage because they absorb CO_2 from the atmosphere during their growth and fix it in their biomass. Therefore, in the case of producing a fuel based on biomass, although CO_2 is emitted during the combustion process, the emissions are offset, ideally resulting in near-net zero GHG emissions from a WtW perspective. CO_2 originated from biomass can therefore be classified as renewable CO_2. Furthermore, in the case of CO_2 captured by DAC technology using renewable energy, atmospheric carbon can be captured without generating any additional GHGs. In other words, the GHG emissions in the production stage can have negative values. Therefore, it can also be classified as renewable CO_2. If this renewable CO_2 is combined with blue hydrogen to produce methanol, most of the WtW GHG emissions will consist of GHG emissions from the blue hydrogen production process alone, resulting in low-carbon blue methanol that has lower GHG emissions than the blue methanol made above from blue hydrogen and non-renewable CO_2.

3) Blue methanol produced from green hydrogen and non-renewable CO_2

Since green hydrogen is produced by electrolyzing water using electricity obtained from renewable energy, the GHG emissions in this process are ideally close to zero. However, if green hydrogen is combined with non-renewable CO_2 released from fossil fuels to make methanol, the CO_2 generated from the combustion of the methanol will be, in the end, non-renewable CO_2 produced from fossil fuels. Therefore, this type of blue methanol cannot have net-zero GHG emissions. However, since the GHG emissions in the production stage ideally converge to zero, it can have lower GHG emissions than the blue methanol mentioned in (1), which is produced using blue hydrogen and non-renewable CO_2.

- Green Methanol: Bio-methanol

Bio-methanol refers to methanol produced from biomass. Biomass here refers a general term for bio-organisms such as plants that receive solar energy to synthesize organic matter using water and CO_2, and animals and microorganisms that take them as food, which can be converted into energy. If methanol is produced from biomass, GHG emissions in production can have negative values due to the absorption of CO_2 in the growth phase, which can offset the amount of GHG emitted in the combustion stage. Therefore, ideally, it is possible to produce green methanol with net-zero GHG emissions. The majority of green methanol produced today is bio-methanol. Bio-methanol can be produced in two main ways, as shown in Figure 2-5.

1) Bio-methanol produced by reforming biogas

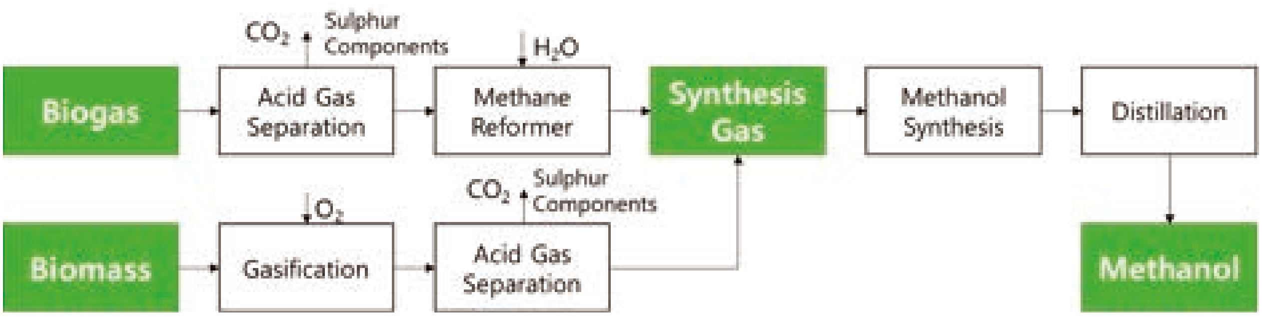
During storage and treatment, various biowastes undergo anaerobic digestion by microorganisms to produce biogas, which consists mainly of a mixture of methane and CO_2. Biogas is generated primarily in the following cases:

- Biogas is formed by the activity of microorganisms in organic matter reservoirs (biodigesters)
- Biogas is formed during the decomposition of municipal solid waste (MSW) in places like waste landfills (landfill gas)
- Biogas is formed by microbial decomposition of organic matter filtered out of sewage during wastewater treatment

The biogas formed as above is a mixture of mainly methane (CH_4) and CO_2, which also contains some sulfur components, so the sulfur components and CO_2 are separated through a pretreatment separation process to make biomethane. The biomethane produced this way is converted into synthesis gas, a mixture of H_2 and CO, through a methane reformer. It is compressed through a compression process and then converted into methanol in the methanol synthesis process. After undergoing a distillation process to remove impurities contained in the converted methanol, methanol is finally produced. According to the European Biogas Association (EBA), approximately 20,000 biogas production processes are known to be operating in Europe as of 2020 [30]. There are approximately 3,500 compressed natural gas (CNG) refueling stations in Europe, of which more than 400 supply biomethane. [29]

2) Bio-methanol produced through reformation after biomass gasification

Gasification technology, which has been traditionally used for coal gasification, can be applied to biomass to convert various biomass feedstocks into syngas and then synthesize it into methanol. Before feeding the gasifier, a pretreatment process of the feedstock is required, and gasification is performed by supplying oxygen separated from the air separation unit (ASU). Depending on the type of gasifier, syngas contains impurities, so impurities such as tar and dust are removed through a subsequent separation process, and sulfur components and CO_2 are separated through an acid gas removal unit (AGRU). The syngas produced is converted into methanol in the methanol synthesis process, and methanol is finally obtained through the distillation process.



|Figure 2-5| Reformer-based methanol production process [29]

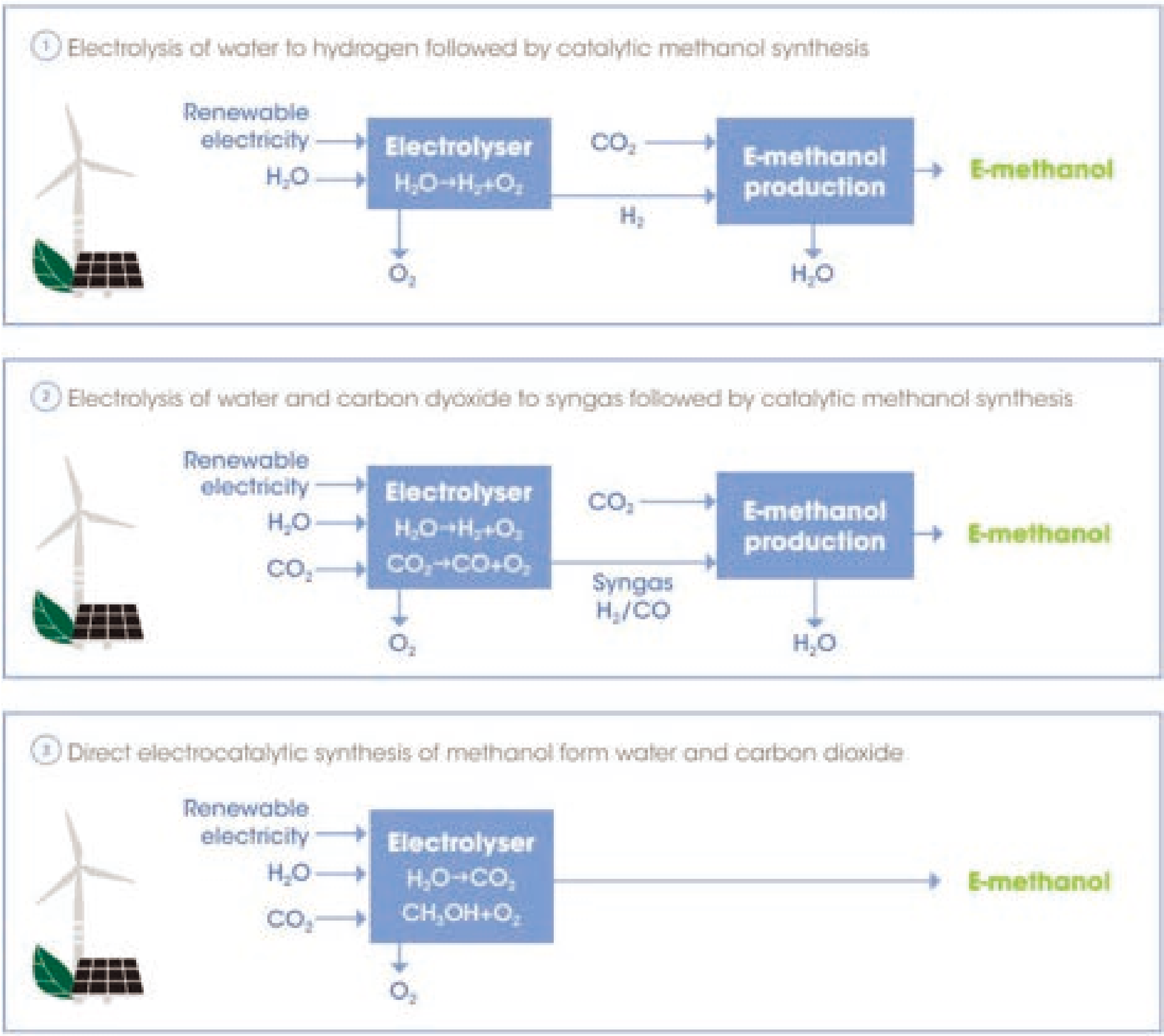
- Green Methanol: E-methanol

E-methanol refers to methanol produced by synthesizing renewable CO_2 and green hydrogen obtained by electrolyzing water through renewable energy-based water electrolysis technology. Therefore, for e-methanol, not only the method of supplying the H_2 used as a feedstock but also the method of supplying CO_2 is very important. Currently, it is discussed that in order to be recognized as an e-fuel, it must be able to achieve a GHG reduction of at least 70% compared to conventional fossil fuels. Thus, it seems that e-methanol can be recognized as an e-fuel only if renewable CO_2 is used as a feedstock along with green hydrogen. For example, non-renewable CO_2 captured from power plants, steel plants, or cement plants is essentially CO_2 generated from the combustion of fossil fuels and therefore contributes to a net-positive CO_2 emissions in terms of WtW emissions. Therefore, it can be a low-carbon blue methanol, but it is unlikely to be an e-methanol that reduces GHG emissions by more than 70%.

Methods for obtaining renewable CO_2 include a method of separating CO_2 emitted from biomass and a method of directly separating CO_2 from the atmosphere using DAC that utilizes renewable energy. Biogas formed from biomass typically contains 20-50% CO_2, and systems using CCS technology to separate, capture, and store such CO_2 are called bioenergy with carbon capture and storage (BECCS) [31]. Therefore, e-methanol can be produced by utilizing BECCS or renewable energy-based DAC to produce renewable CO_2 and then synthesizing it with green hydrogen.

In Denmark, the Green Fuels for Denmark (GFDK) project has been established and aims to achieve 10 MW of electrolysis capacity to produce green hydrogen in 2023, 250 MW in 2027, and 1.3 GW in 2030. The green hydrogen produced will be combined with renewable CO_2 from MSW or biomass to produce renewable methanol (e-methanol) for use in ships and renewable jet fuel (e-kerosene) for aircraft [29, 32].

Research is underway to produce e-methanol by various pathways. In Figure 2-6, ① shows currently the most commonly considered e-methanol production method. It uses water electrolysis to produce green hydrogen and then synthesizes methanol by reacting H2 with CO_2. ② and ③ show methods that produce e-methanol with fewer steps by supplying H_2O and CO_2 as feedstocks in the electrolysis step. In method ②, H_2O is separated into H_2 and oxygen (O_2) in water electrolysis, and CO_2 is separated into CO and O_2 to produce syngas (H_2 and CO). It is then used with CO_2 to synthesize methanol. In method ③, methanol is directly synthesized through direct electrochemical conversion of H_2O and CO_2. Since this method, if commercialized, could simplify the methanol production process, many studies are currently underway, but they are still limited to laboratory-scale capacity.



|Figure 2-6| E-methanol production methods [29]

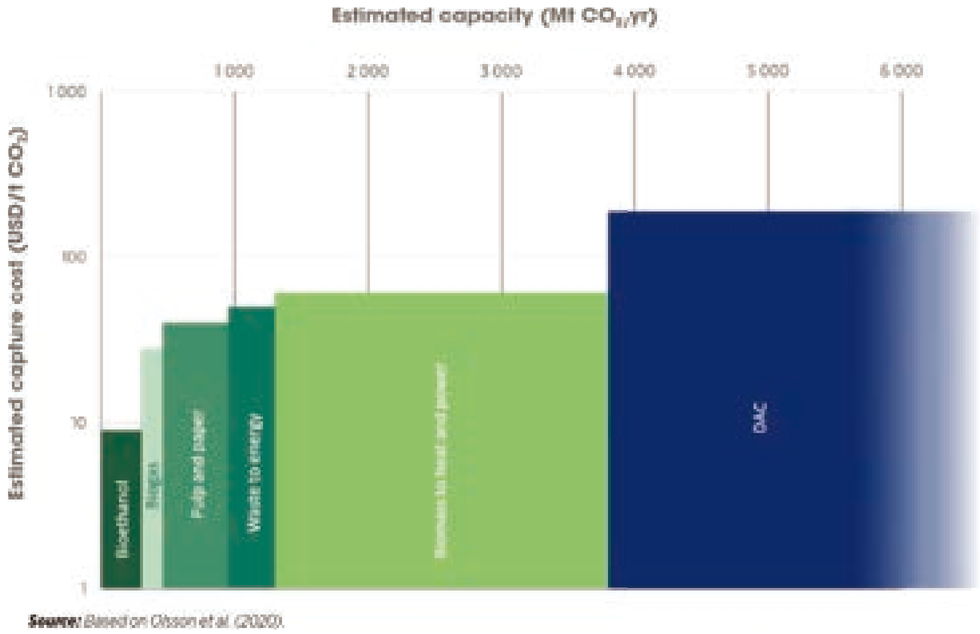
- Problems of Supply Sources and Capacity for Renewable CO_2

As discussed earlier, the type of CO_2 source for methanol synthesis is an important factor in estimating GHG emissions to produce e-methanol. Table 2-4 [29] shows the concentration range of CO_2 captured according to the supply source. If biomass and biogas are used, relatively high purity CO_2 can be obtained, which means that relatively little energy is required to capture CO_2. However, in the case of biogas, as shown in Figure 2-7, the capacity of the source is limited, and the time required for supply may be discontinuous, which needs to be taken into consideration. There is also a limitation that methanol production facilities must be located in close proximity to where CO_2 is generated, which can limit the places for methanol production.

If DAC is used to capture CO_2, it can be used anywhere on Earth and is free from capacity limitations. However, in order to qualify as renewable CO_2, all of the power used for DAC must be supplied from renewable energy, and since the concentration of CO_2 in the atmosphere is very low, the energy required to capture CO_2 is high. Therefore, there is a problem that the cost of supplying CO_2 using DAC can increase significantly, which in turn increases the cost of e-methanol.

[Table 2-4] Captured CO_2 concentration and CO_2 type by supply source [29]

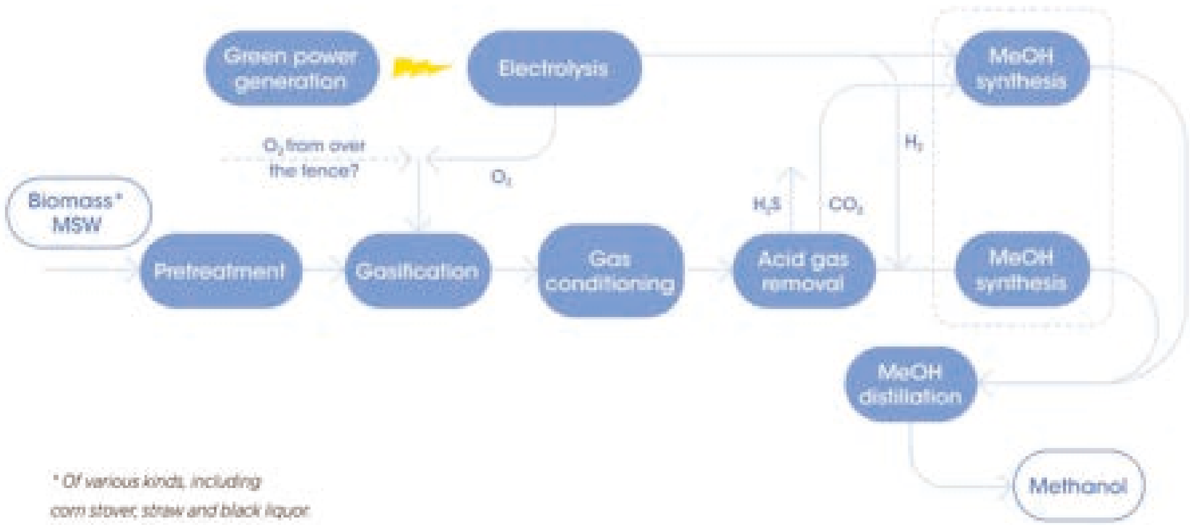
CO_2 Source	CO_2 Concentration (%) When Captured	Renewable/Non-renewable CO_2 Classification
Biomass to ethanol	Up to 100	Renewable CO_2
Biomass combustion	3-8	Renewable CO_2
Biomass gasification	20-90	Renewable CO_2
Biogas	40-50	Renewable CO_2
BECCS	Close to 100	Renewable CO_2
DAC (only if powered by renewable energy)	0.042	Renewable CO_2
Coal power plant	12-14	Non-renewable CO_2
Coal power plant with oxy-combustion	Close to 100	Non-renewable CO_2
Natural gas power plant	3-5	Non-renewable CO_2
Iron and steel plant	20-30	Non-renewable CO_2
Cement plant	15-30	Non-renewable CO_2
Natural gas purification	2-65	Non-renewable CO_2
Ammonia synthesis	Up to 100	Non-renewable CO_2



|Figure 2-7|Estimated capacity of renewable CO_2 from various supply sources up to the mid-21st century [29, 33]

- Hybrid Process of Bio-methanol and E-methanol

With the technology development of bio-methanol and e-methanol processes, research and development on hybrid processes are also underway to maximize carbon conversion efficiency by integrating the two processes. When producing methanol from biomass, only about 50% of the carbon in the feedstock is converted to methanol, with the remainder existing as CO_2. Therefore, if the bio-methanol and e-methanol processes are integrated, as shown in Figure 2-8, the CO_2 emitted to the atmosphere can be further utilized for methanol production, and related studies are underway.



|Figure 2-8| Hybrid-process example of bio-methanol process and e-methanol process [29]

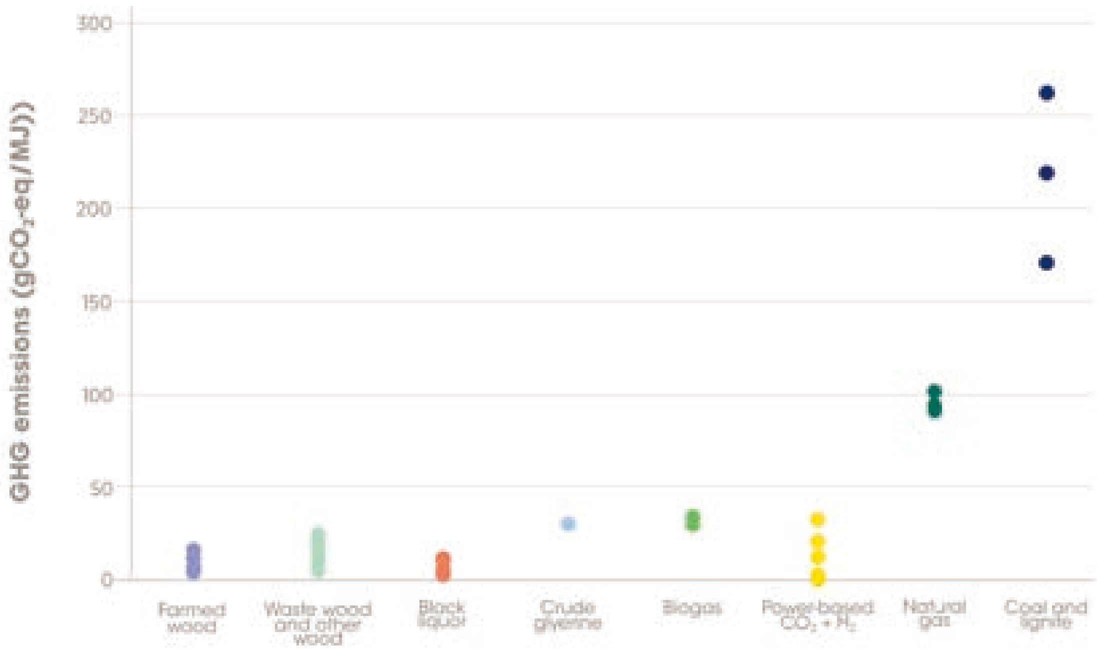
2.3. WtW GHG Emissions Intensity of Methanol and Other Fuels

- GHG Reduction Effects of Bio-methanol and E-methanol

As examined earlier, methanol production processes vary widely, so the WtW GHG emissions of a fuel estimated through LCA vary significantly depending on how the feedstock and production process are defined. Furthermore, even when similar feedstocks and processes are used, the estimated GHG emissions can be different between different researchers or organizations depending on the adopted assumption. As an example, Figure 2-9 shows a wide range of differences in GHG emissions among different feedstocks of methanol.

When estimating WtW GHG emissions for biofuels, it is important to consider the impact of land use change (LUC). In addition to direct land use change (DLUC) for the cultivation of feedstock crops for biofuels, GHG emissions from indirect land use change (ILUC), which occurs as existing crops are changed, have recently become controversial. Therefore, when assessing the GHG emissions of biofuels such as bio-methanol, it is important to note that GHG emissions can increase significantly if the environmental impacts of LUC are included.

In the case of e-methanol, GHG emissions can also vary significantly depending on the pathway and feedstock used in the production process. As an example, Table 2-5 shows that e-methanol can have low levels of GHG emissions intensity compared to conventional fossil fuels, but the values can vary widely.



|Figure 2-9| Summary of life-cycle GHG intensity by feedstock of methanol (LUC not included) [29]

[Table 2-5] Example of WtW GHG emissions intensity for electricity-based e-methanol production pathways [29]

Feedstock	WtW GHG emissions intensity (g_{CO2eq}/MJ)
Renewable electricity, flue gas from biogas plant	0.5
Renewable electricity, flue gas from biomass plant	1.74-3.23
Renewable electricity, CO_2 from ethanol plant	13-21.3
Renewable electricity, CO_2 captured from coal power plant	33.1
Renewable electricity, flue gas (geothermal energy plant)	12.1

- Life-cycle GHG Emissions Intensity of Marine Fuel Based on FuelEU Maritime

In July 2021, the European Commission proposed legislation to achieve GHG reductions in the shipping sector through the gradual adoption of alternative marine fuels. This is the FuelEU Maritime included in the Fit-for-55 package. As shown in Table 2-6 [34], the proposed regulation demands to reduce the GHG intensity of ships over time. In this section, a life-cycle GHG emissions intensity of different marine fuels is analyzed based on the FuelEU Maritime-based calculation guidelines.

The global warming potential (GWP) used in this analysis is the GWP over a 100-year time horizon (GWP 100) provided by the Directive (EU) 2018/2001 (hereinafter RED II) in accordance with the FuelEU Maritime Directive, and it is based on the GWP 100 of the IPCC Fourth Assessment Report [7]. However, as shown in Table 2-7, the GWP is constantly being revised based on research results, and the GWP100 in the latest IPCC report is different from the current value used in FuelEU Maritime/RED II. Therefore, it is important to note that changing the reference value may cause differences in GHG calculation results.

Table 2-8 shows the WtW GHG intensity for conventional fossil fuels, biofuels, and e-fuels. In the case of e-fuels, WtW GHG emissions intensity are highly variable depending on the renewable energy and feedstock conditions in the production area. Therefore, this document assumes a reduction of 70% compared to the WtW GHG baseline emissions of fossil fuels (IMO 94 g_{CO2eq}/MJ), which is the GHG reduction threshold proposed by RED II to be recognized as an e-fuel. In other words, the WtW GHG emissions must be 28.2 g $_{CO2eq}$/MJ or less to qualify as an e-fuel, and the qualifiable WtT GHG emissions were calculated based on this.

[Table 2-6] FuelEU Maritime's initial GHG intensity reduction targets and recently strengthened reduction targets [34]

Target year	Commision proposal (2021)	Amendment
2020 (baseline)	91.16 g $_{CO2\text{-}eq}$/MJ	
2025	−2% (89.3 g $_{CO2\text{-}eq}$/MJ)	−2% (89.3 g $_{CO2\text{-}eq}$/MJ)
2030	−6% (85.7 g $_{CO2\text{-}eq}$/MJ)	−6% (85.7 g $_{CO2\text{-}eq}$/MJ)
2035	−13% (79.3 g $_{CO2\text{-}eq}$/MJ)	−14.5% (77.9 g $_{CO2\text{-}eq}$/MJ)
2040	−26% (67.5 g $_{CO2\text{-}eq}$/MJ)	−31% (62.9 g $_{CO2\text{-}eq}$/MJ)
2045	−59% (37.4 g $_{CO2\text{-}eq}$/MJ)	−62% (34.6 g $_{CO2\text{-}eq}$/MJ)
2050	−75% (22.8 g $_{CO2\text{-}eq}$/MJ)	−80% (18.2 g $_{CO2\text{-}eq}$/MJ)

[Table 2-7] GWP 100 by IPCC reports [3]

Substance	GWP100			
	IPCC 4th Report (AR4, 2007)	IPCC 5th Report (AR5, 2014)	IPCC 6th Report (AR6, 2022)	Value Used in RED II /FuelEU Maritime
CO_2	1	1	1	1
CH_4	25	28, 34	29.8 (based on fossil fuels)	25
			27.2 (non-fossil fuels)	
N_2O	298	265, 298	273	298

[Table 2-8] Life-cycle GHG emissions intensity of marine fuels based on FuelEU Maritime.

Fuel Class	Pathway name	LHV (MJ/g)	WtT intensity (g CO_2eq /MJ)	Fuel ConsumerUnit Class	TtW intensity (g CO_2eq /MJ)	WtW intensity (g CO_2eq /MJ)	WtW intensity incl. ILUC[2] (g CO_2eq /MJ)	Source
Fossil	HFO (ISO 8217 Grades RME to RMK)	0.0405	13.5	All ICEs	78.2	91.7	-	FuelEU Mari-time (EU, 2023)
	LFO (ISO 8217 Grades RMA to RMD)	0.041	13.2		78.2	91.4	-	
	MDO/MGO (ISO 8217 DMX to DMB)	0.0427	14.4		76.4	90.8[1]	-	
	LNG (Liquified Natural Gas)	0.0491	18.5	LNG Otto(DFMS)	70.7	89.2	-	
				LNG Otto(DFMS)	64.4	82.9	-	
				LNG Otto(DFMS)	57.6	76.1	-	
				LBSI	68.4	86.9		
	LPG (Liquified Petroleum Gas)[3]	0.046	7.8	ICE (Butane)	65.9	73.7	-	
				ICE (Propane)	65.2	73.0	-	
	H2 (from natural gas)[3]	0.12	132.0	ICE/Fuel Cells	0.0	132.0	-	
	NH3 (from natural gas)[3]	0.0186	121.0	ICE/Fuel Cells	0.0	121.0	-	
	Methanol (from natural gas)[3]	0.0199	31.3	ICE	69.1	100.4	-	
bio-Ethanol[3]	Sugar beet ethanol	0.027	-55.2 to 0.8	All ICEs	70.9	22.5-50.2	35.5-63.2	RED II (EU, 2018) / FuelEU Mari-time (EU, 2023)
	Corn (maize) ethanol					30.3-67.8	42.3-79.8	
	Other cereals excluding maize ethanol					31.4-71.7	43.4-83.7	
	Sugar cane ethanol					28.6	41.6	
	Wheat straw ethanol					15.7	-	
bio-Diesel[3]	Crop biodiesel	0.0372	-61.7 to -0.9	All ICEs	76.6	44.7-50.1	56.7-62.1	
	Oil crop biodiesel					51.6-75.7	106.6-130.7	
	Waste cooking oil biodiesel					14.9	-	
	Animal fats from rendering biodiesel					20.8	-	
	Fischer-Tropsch diesel	0.044	-54.2 to -47.7		64.4	11.7-18.2	-	
Hydro-treated vegetable oil (HVO)	Crop HVO	0.044	-54.8 to 2.5	All ICEs	72.0	44.8-51.3	56.8-63.3	
	Oil crop HVO					49.2-74.5	104.2-129.5	
	Waste cooking oil HVO					17.2	-	
	Animal fats from rendering HVO					23.0	-	
bio-Methanol[3]	Waste wood methanol in free-standing plant	0.02	-55.3	All ICEs	68.8	10.4	-	
	Farmed wood methanol in free-standing plant		-52.6			13.5	-	
	Methanol from black-liquor gasification integrated with pulp mill		-58.4			16.2	-	

Fuel Class	Pathway name	LHV (MJ/g)	WtT intensity (g CO_{2eq} /MJ)	Fuel ConsumerUnit Class	TtW intensity (g CO_{2eq} /MJ)	WtW intensity (g CO_{2eq} /MJ)	WtW intensity incl. ILUC[2] (g CO_{2eq} /MJ)	Source
bio-Methane[4]	Wet manure	0.05	-155.0 to -33.0	Wet manure	0.05	-85.6 to 36.4	-	RED II (EU, 2018) / FuelEU Maritime (EU, 2023)
	Maize whole plant		-25.0 to 18.0			44.4-87.4	56.4-99.4	
	Biowaste		-41.0 to 16.0			28.4-85.4	-	
	Wet manure		-155.0 to -33.0	Wet manure		-91.8 to 30.2	-	
	Maize whole plant		-25.0 to 18.0			38.2-81.2	50.2-93.2	
	Biowaste		-41.0 to 16.0	LBSI	67.2	22.2-79.2	-	
	Wet manure		-155.0 to -33.0	LNG Diesel(DFSS)	56.5	-98.5 to 23.5	-	
	Maize whole plant		-25.0 to 18.0			31.5-74.5	43.5-86.5	
	Biowaste		-41.0 to 16.0			15.5-72.5	-	
	Wet manure		-155.0 to -33.0	LBSI	67.2	-87.8 to 34.2	-	
	Maize whole plant		-25.0 to 18.0			42.2-85.2	54.2-97.2	
	Biowaste		-41.0 to 16.0			26.2-83.2		
Renewable Fuels of Non-Biological Origin (RFNBO) - (e-fuels)	e-diesel	0.0427	Below -48.2	ICE	76.4	Below 28.2 Based on 70% reduction[5]	-	RED II (EU, 2018) / FuelEU Maritime (EU, 2023)
	e-methanol	0.0199	Below -40.9	ICE	69.1		-	
	e-LNG	0.0491	Below -42.5	LNG Otto(DFMS)	70.7		-	
			Below -36.2	LNG Otto(DFMS)	64.4		-	
			Below -29.4	LNG Diesel(DFSS)	57.6		-	
		0.12	Below -40.2	LBSI	68.4			
	e-H_2	0.12	Below 28.2	ICE/Fuel Cells	0.0		-	
	e-NH_3	0.0186	Below 28.2	ICE/Fuel Cells	0.0		-	
Others	Electricity (EU MIX 2020)	-	106.3	OPS	-	106.3	-	EU, 2021
	Electricity (EU MIX 2030)	-	72	OPS	-	72	-	

LHV: lower heating value; ICE: internal combustion engine; DFMS: dual fuel medium speed; DFSS: dual fuel slow speed; LBSI: lean-burn spark ignition; OPS: On-shore power supply; ILUC: Indirect land use change.

1) Current IMO fossil fuel WtW GHG intensity baseline of 94 g_{CO2eq}/MJ are not the same as the FuelEU Maritime (91.2 g_{CO2eq}/MJ).
2) The estimated result of WtW emissions intensity of biofuels when emissions due to indirect land use change (ILUC) are included.
3) Impact of GHGs other than CO_2 emitted during combustion (CH_4, N_2O) is not currently included (not currently pro-

vided in the FuelEU Maritime Directive) - may be revised in the future.

4) Energy consumption of the liquefaction process is not included

5) Based on RED II, the qualification criteria for e-fuel and bio-fuel are 70% and 65% reduction to fossil fuel WtW GHG emissions intensity.

03

Methanol Regulations and Standards for Ships

3.1. International Regulations

Because of the need for a variety of fuels, coupled with strengthened international regulations, the IMO amended the International Code of Safety for Ships using Gases or other Low-flashpoint Fuels (IGF Code), which was previously applicable to LNG ships, to include other low-flashpoint fuels [35-36]. In 2020, the IMO approved IMO MSC.1/Circular.1621 "Interim Guidelines for the Safety of Ships Using Methyl/Ethyl alcohol as Fuel" to reflect the increased demand for methanol-fueled ships. Currently, methanol-fueled ships follow the Interim Guidelines.

MSC.1/Circular.1621 is interim guidelines based on the IGF Code and expanded to be applicable to methanol-fueled ships based on Part A-1 of the IGF Code, which is defined for conventional natural gas ships. Table 3-1 shows the highlights.

[Table 3-1] IMO MSC.1/Circular.1621 Interim Guidelines for the Safety of Ships Using Methyl/Ethyl alcohol as Fuel

1 Introduction It states that the main purpose of these guidelines (1.1) is to provide an international standard for ships using methyl/ethyl alcohol (methanol/ethanol) as fuel, and describes the main philosophy of following the goal-based approach (1.4, MSC.1/Circ.1394/Rev.2).
2 General It describes those subjected to the application (2.1) of the guidelines, definitions (2.2), and provides requirements for the alternative design (2.3).
3 Goal and functional requirements It describes the goal (3.1) of the guidelines and specific functional requirements (3.2).
4 General provisions It describes the risk assessment (4.2) and the limitation of explosion consequences (4.3).
5 Ship design and arrangement It describes the functional requirements (5.2) for the ship design and arrangement required for safety and also describes provisions for independent fuel tanks (5.4), portable tanks (5.5), machinery space (5.6), fuel piping (5.7), fuel preparation spaces (5.8), bilge systems (5.9), drip trays (5.10), enclosed spaces (5.11), and airlocks (5.12).
6 Fuel containment system It describes the functional requirements (6.2) of fuel containment system and provisions for fuel tanks venting and gas freeing system (6.3), inerting (6.4), and inert gas availability (6.5).

7 Material and general pipe design It describes the functional requirements (7.2) of materials and piping and provisions for pipe design (7.3) and materials (7.4).
8 Bunkering It describes the functional requirements (8.2) of bunkering and provisions for bunkering station and bunker hoses (8.3), manifold (8.4), and bunkering system (8.5).
9 Fuel supply to consumers It describes the functional requirements (9.2) of fuel supply system and provisions for fuel supply system (9.3), fuel distribution (9.4), redundancy of fuel supply (9.5), safety functions (9.6), and fuel preparation spaces and pumps (9.7).
10 Power generation including propulsion and other energy converters It describes the functional requirements (10.2) of power generation including propulsion and other energy converters and provisions for dual-fuel engines (10.4) and single-fuel engines (10.5).
11 Fire safety describes the functional requirements (11.2), provisions for fire safety (11.3), fire protection (11.4), fire main (11.5), fire fighting (11.6), and fire extinguishing of engine-room and fuel preparation space (11.7).
12 Explosion prevention and area classification It describes the functional requirements and general provisions for explosion preparation and area classification (12.2, 12.3) and provisions for area classification (12.4) and hazardous area zones (12.5).
13 Ventilation It describes the functional requirements and general provisions for ventilation (13.2, 13.3) and provisions for fuel preparation spaces (13.4), bunkering station (13.5), and ducts and double wall pipes (13.6).
14 Electrical installations It describes the functional requirements and general provisions for electrical installations (14.2, 14.3).
15 Control, monitoring and safety systems It describes the functional requirements and general provisions for controls, monitoring, and safety systems (15.2, 15.3) and provisions for bunkering and fuel tank monitoring (15.4), bunkering control (15.5), engine monitoring (15.6), gas (fuel vapor) detection (15.7), fire detection (15.8), ventilation (15.9), and safety functions of fuel supply systems (15.10).
16 Training, drills and emergency exercises It describes the requirements for shipboard training, drills, and emergency exercises for mariners.
17 Operation It describes the functional requirements (17.2) of operational regulations, provisions for maintenance (17.3) and bunkering operations (17.4).

3.2. Regulations in South Korea

Considering the seriousness of the problem of pollutant and GHG emissions from ships, the South Korean government enacted the "Act on Promotion of Development and Distribution of Environmentally-Friendly Ships" (also known as the "Green Ship Act") in 2018, which has been in effect since 2020. Accordingly, a ship passing the certification procedure can receive Korean government certification as an environment-friendly ship. As shown in Table 3-2, the Green Ship Act Article 2 Subparagraph 3 allows that ships using various technologies and alternative fuels can be included as environmentally-friendly ships. The specific regulation on "green energy" referred here is based on the "Regulation on Standards and Certification of Environmentally-Friendly Ships", a joint decree of the Korean Ministry of Oceans and Fisheries and the Korean Ministry of Trade, Industry and Energy. Article 3 of the regulation specifies that methanol can be used as eco-friendly energy as defined by the Green Ship Act, as shown in Table 3-2.

[Table 3-2] Green Ship Act and related regulations in South Korea

Act on Promotion of Development and Distribution of Environment-Friendly Ships (Green Ship Act)

Article 2 (Definitions). The definitions of terms used in this Act shall be as follows.

3. The term "green ship" refers to a ship that falls under any of the following items:
    - A. A ship designed by applying technology that reduces marine pollution or using technology that can increase the energy efficiency of the ship and meets the standards set by a joint ministerial decree of the Ministry of Trade, Industry and Energy and the Ministry of Oceans and Fisheries (hereinafter referred to as "Joint ministerial Decree").
    - B. Ships that use environmentally friendly energy as a power source, such as liquefied natural gas, as set by the Joint ministerial Decree.
    - C. Electric propulsion ships powered by electric energy charged from a power supply source.
    - D. Hybrid vessels powered by a combination of electric energy (including electric energy charged from a power supply source) and gasoline/diesel/liquefied petroleum gas/natural gas/fuels specified by the Joint ministerial Decree.
    - E. Fuel cell-powered ships that use electric energy generated using hydrogen as a power source.

Regulation on Standards and Certification of Environment-Friendly Ships

Article 3 (Green Energy). In Article 2 Subparagraph 3 Item D of the Act (Green Ship Act), "green energy, such as liquefied natural gas, as defined by the Joint Ministerial Decree" means energy that falls under any of the following items:

1. Liquefied natural gas (LNG)
2. Compressed natural gas (CNG)
3. Liquefied petroleum gas (LPG)
4. Methanol
5. Hydrogen
6. Ammonia
7. Other energy recognized by the Minister of Trade, Industry and Energy and the Minister of Oceans and Fisheries as necessary to create a clean marine environment

In 2020, after the enactment of the Act, the government established the "2030 Korean Green Ship Promotion Strategy," a national basic plan with a 10-year plan until 2030, through data collection and analysis and consultation with expert groups. It has the goal of "securing world-leading technology for future eco-friendly ships" and "reducing GHG emissions from ships and creating eco-friendly new markets", and specifies six major tasks, as shown in Table 3-3.

[Table 3-3] Six major tasks in the 2030 Korean Green Ship Promotion Strategy

1. Secure world-leading technology for future eco-friendly ships (1) Secure carbon-free ship technologies such as hydrogen and ammonia technologies (2) Develop low-carbon ship technologies such as mixed-fuel propulsion technologies (3) Enhance LNG, electric, and hybrid propulsion technologies
2. Build a test-bed to spread new technologies (1) Prepare test and inspection standards (2) Build test and evaluation facilities
3. Implement the South Korean pilot project (Green Ship-K) (1) Build a field-test ship for Green Ship-K (2) Validate technologies and support market penetration through marine field-tests
4. Expand fuel supply infrastructure (1) Expand fuel supplies for LNG ships (2) Build carbon-free fuel supply infrastructure
5. Promotion of green ships (1) Preemptive conversion in the public sector (2) Expand the conversion in the private sector

6. Create a green ship market-led ecosystem (1) Support international standardization of South Korean new technologies (2) Prepare a digital/statistics-based ship operation system

- The Rules of the Korean Register (KR)

Annex 5 of the Rules for Ships Using Low-flashpoint Fuels applies to ships using methyl/ethyl alcohol as fuel. (Chapter 1, 101.4 of the Rules for Ships Using Low-flashpoint Fuels) Annex 5, "Requirements for Ships Using Methyl/Ethyl Alcohol as Fuel (2021)", has been prepared in accordance with the IMO's Interim Guidelines MSC.1/Circular.1621 (Interim Guidelines for the Safety of Ships Using Methyl/Ethyl Alcohol as Fuel). The important points for methanol-fueled ships mentioned in the Rules for Ships Using Low-flashpoint Fuels are summarized in Tables 3-4 below. (See Section 5.3 for a discussion of key safety rules.)

[Table 3-4] Highlights of the Rules for Ships Using Low-flashpoint Fuels

Chapter 1 General "101. Application" in Section 1 specifies the following: 101. Application 4. Annex 5 applies to ships using methyl/ethyl alcohol as fuel. (2021)
Chapter 2 Goal and Functional Requirements It describes the goal of these Rules (101) and functional requirements (201).
Chapter 3 General Requirements It describes the risk assessment (201) and the limitation of explosion consequences (301).
Chapter 4 Classification and Surveys It describes the class notations (201), maintenance of classification (202), classification survey during construction (203), annual survey (301), intermediate survey (302), special survey (303). In class notations, the notations of ships using methyl/ethyl alcohol as fuel are defined as follows: 201. Class notations Ships satisfying the requirements of this Rules may be given a notation "LFFS" as additional special feature notations and details are as follows. (2021) 1. LFFS(DF-LNG): Dual fuel engines using LNG as fuel are installed 2. LFFS(SF-LNG): Single fuel engines using LNG as fuel are installed 3. LFFS(DF-Methanol): Dual fuel engines using methyl alcohol as fuel are installed 4. LFFS(SF-Methanol): Single fuel engines using methyl alcohol as fuel are installed 5. LFFS(DF-Ethanol): Dual fuel engines using ethyl alcohol as fuel are installed 6. LFFS(SF-Ethanol): Single fuel engines using ethyl alcohol as fuel are installed

[Table 3-5] Highlights of Annex 5 "Requirements for Ships Using Methyl/Ethyl Alcohol as Fuel" (2021)

Section 1 General It describes those subjected to the application of Annex 5 (101), definitions of terms (102), and requirements of alternative design (103). 101. Application The requirements of this Annex apply to ships using methyl/ethyl alcohol as fuel.
Section 2 Goal and Functional Requirements It describes specific functional requirements (202).
Section 3 General Requirements It describes the requirements for risk assessment (302) and the limitation of explosion consequences. The limitation of explosion consequences (303) is based on the requirements specified in Chapter 3, 301 of the Rules and Guidance for Ships Using Low-flashpoint Fuels.
Section 4 Classification and Surveys It describes the class notations (402), maintenance of classification (403), classification survey during construction (404), and periodical surveys (405).
Section 5 Ship Design and Arrangement It describes the functional requirements for ship design and arrangement (502) and arrangement, specifications, and requirements for fuel containment system (503), independent fuel tanks (504), portable tanks (505), machinery space (506), fuel piping (507), fuel preparation spaces (508), bilge systems (509), drip trays (510), entrances and other openings in enclosed spaces (511), and airlocks (512).
Section 6 Fuel Containment System It describes the functional requirements for fuel containment system (602) and the requirements for fuel tanks venting and gas freeing system (603), inerting and environmental control (604), and inert gas availability on board (605).
Section 7 Material and General Pipe Design It describes the functional requirements for materials and piping (702) and the provisions for pipe design (703) and materials (704).
Section 8 Bunkering It describes the functional requirements for bunkering (802) and the requirements for bunkering station and fuel hoses (803), manifold (804), and bunkering system (805).
Section 9 Fuel Supply to Consumer It describes the functional requirements (902), general requirements for fuel supply system (903), requirements for fuel distribution (904), redundancy of fuel supply (905), safety functions (906), and requirements for fuel preparation spaces and pumps (907).

Section 10 Power Generation Including Propulsion and Other Energy Converters

It describes the functional and general requirements for power generation and other equipment (1002, 1003) and the requirements for dual-fuel engines (1004) and single fuel engines (1005).

Section 11 Fire Safety

It describes the functional and general requirements for fire safety (1102, 1103) and the requirements for fire protection (1104), fire main (1105), fire fighting (1106), and fire extinguishing of engine-room and fuel preparation space (1107).

Section 12 Explosion and Area Classification

It describes the functional and general requirements for explosion prevention and area classification (1202, 1203) and the requirements for area classification (1204) and hazardous area zones (1205).

Section 13 Ventilation

It describes the functional and general requirements for ventilation (1302, 1303) and the ventilation requirements for fuel preparation spaces (1304), bunkering station (1305), and ducts and double wall pipes (1306).

Section 14 Electrical Installations

It describes the functional and general requirements for electrical installations.

Section 15 Control, Monitoring, and Safety Systems

It describes the functional and general requirements for control, monitoring, and safety systems (1502, 1503) and the requirements for bunkering and fuel tank monitoring (1504), bunkering control (1505), engine monitoring (1506), fuel vapor detection (1507), fire detection (1508), ventilation (1509), and safety functions of fuel supply systems (1510).

Section 16 Training, Drills and Emergency Exercises

It describes the requirements for onboard training, drills, and emergency exercises (1601).

Section 17 Operation

It describes the functional requirements for operation (1702) and the requirements for maintenance (1703) and responsibilities for bunkering operation (1704).

Section 18 Requirements for Methyl Alcohol and/or Ethyl Alcohol Fuel Ready (2022)

This section states that this Guidance applies to ships which are prepared in advance during the new building phase for the purpose of a conversion to a ship using methyl alcohol and/or ethyl alcohol fuel after delivery (1801). Furthermore, it describes the class notations (1802), requirements for preparation levels (1803), and requirements for survey (1804).

04

Methanol-fueled Ship Technology

4.1. The Status of Methanol Engines

Methanol can reduce smoke and NOx emissions when burned at high temperatures, and it emits very little SOx because it has little sulfur content. It emits less carbon dioxide than HFO and has fuel flexibility in that carbon neutrality can be achieved by gradually increasing the proportion of environmentally friendly methanol such as green, blue, and bio-methanol. However, it is difficult to use methanol alone in diesel engines due to difficulties in starting at low temperatures and operating with low loads [37]. Therefore, marine methanol dual-fuel engines are being developed by using conventional marine fuels such as MGO as a pilot fuel in a way that helps the combustion of methanol [38]. Although dual-fuel engines can be more expensive to install and maintain than single-fuel engines, they offer the flexibility to switch fuels based on market conditions. For these reasons, methanol dual-fuel engines are being developed or have been developed by various engine developers. The status of methanol engines by engine developer is shown in Table 4-1, followed by a detailed description of the major players.

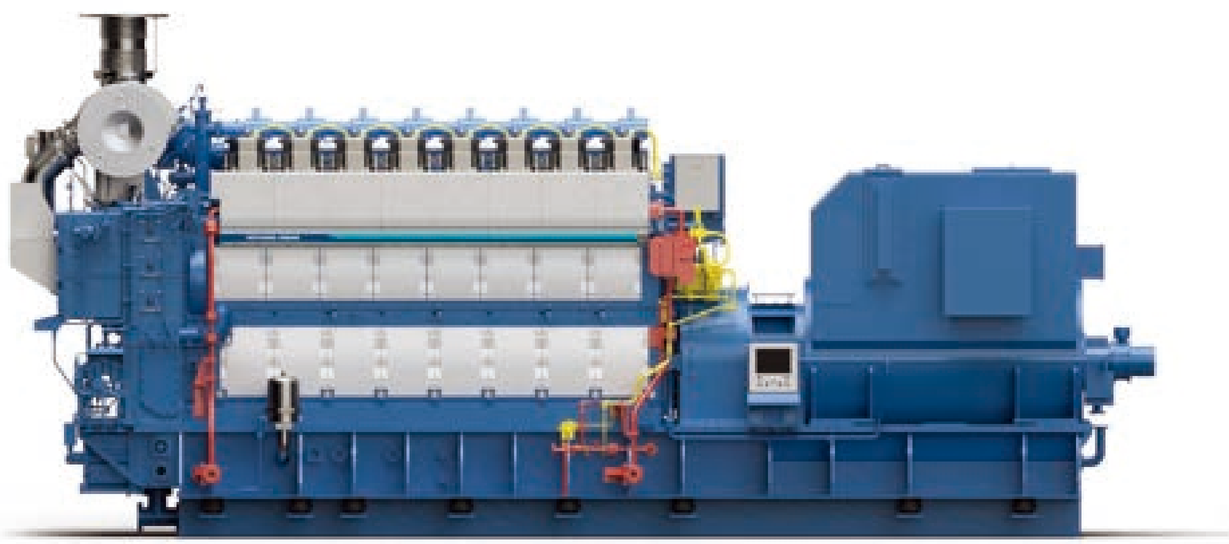
[Table 4-1] The status of methanol engine development by engine developer [39]

Anglo Belgian Corporation (ABC)	Developed the DZD methanol engine family, consisting of 6- and 8-cylinder inline engines and 12- and 16-cylinder V-engines with outputs ranging from 955 kW to 3,536 kW [40].
Caterpillar	Cat® 3500E Series engines can be converted to methanol-fueled propulsion engines.
China State Shipbuilding Corporation (CSSC) Power Research Institute, Anqing CSSC Diesel Engine, and Hudong Heavy Machinery	Developed the M320DM methanol-fueled engine, which can be applied to a wide range of vessels up to 20,000 GT.
Hyundai Heavy Industries - Engine & Machinery Division (HHI-EMD)	Developed a 5,400-hp methanol dual-fuel power generation engine and received orders more than 50 engines (as of October 2022).
MAN Energy Solutions	Completed development of ME-LGIM, a two-stroke methanol dual-fuel engine (accumulated over 145,000 operating hours) and is developing a four-stroke methanol engine.
mtu Marine solutions (by Rolls-Royce)	Will launch a methanol engine based on the MTU Series 4000 in 2026 and a methanol fuel cell in 2028.

Nordhavn Power Solutions A/S	Partnered with ScandiNAOS to offer 13L/6-cylinder and 16L/8-cylinder methanol engines.
Wärtsilä	Completed development of ZA40S and W32 methanol engines based on methanol engine operation experience accumulated since 2015. It will also develop W20 and W46 methanol engines.
WinGD and HSD Engine	Will complete methanol engine development in 2024 through a joint development project.

- HD Hyundai Heavy Industries (HD HHI)

In 2015, HD HHI built a large methanol dual-fuel engine (6G50ME-B9.3-LGIM) and installed it on the world's first 50K methanol carrier/propulsion vessel built by Hyundai Mipo Dockyard (shipowner Westfal-Larsen). Furthermore, HD HHI's Engine & Machinery Division announced in August 2021 that it has received a contract from A.P. Møller - Maersk to equip eight 16,000 TEU class methanol-fueled mega container ships, the next generation of eco-friendly vessels, with methanol dual-fuel heavy-duty engines (Hyundai-MAN B&W 8G95ME-C10.5-LGIM) and HiMSEN methanol dual-fuel medium-duty engines (HiMSEN 6&9H32DF-LM). This contract marks the first application of methanol dual-fuel engines on mega container ships, following Maersk's June 2021 order to Hyundai Mipo Dockyard for a 2,100 TEU class methanol-fueled small container ship with a methanol main engine (6G50ME-C9.6-LGIM) and power generation engine (HiMSEN 6H32DF-LM) [41].

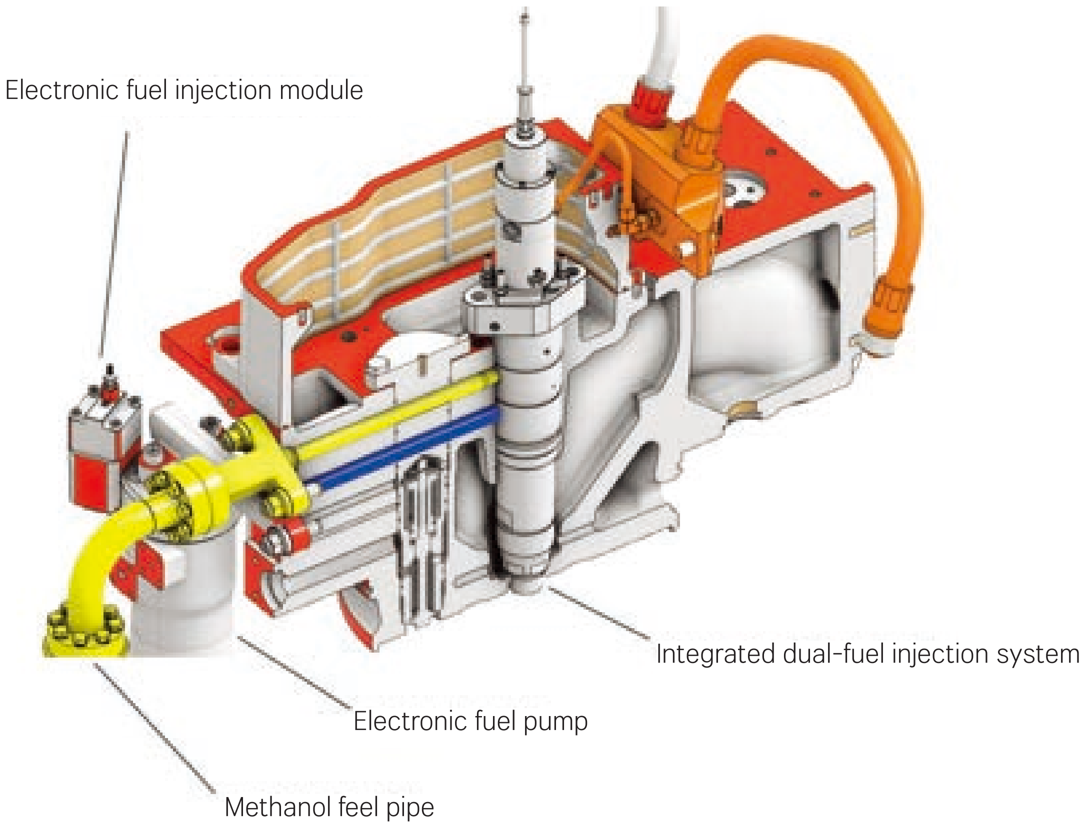


|Figure 4-1| HD HHI's HiMSEN H32DF-LM methanol dual-fuel medium-duty engine

HD HHI announced in September 2022 that it completed the development of a methanol dual-fuel HiMSEN engine (model name: HiMSEN H32DF-LM) and successfully completed the Type Approval Test (TAT) and Factory Acceptance Test (FAT) in the presence of seven classification societies including KR (Korea), ABS (United States), and DNV-GL (Norway-Germany). Furthermore, in December 2022, the company successfully completed factory commissioning tests for methanol dual-fuel medium-duty engines in the presence of a shipowner (A.P. Møller - Maersk) [42-43]. The 2,100 TEU small container ship Laura Maersk, powered by this engine, departed Ulsan in July 2023 and sailed a total of 21,500 km, arriving in Copenhagen, Denmark, where she completed her commissioning and was delivered to the shipowner.

The H32DF-LM engine is a 5,400 hp (3.0-4.5 MW) dual-fuel engine that can selectively run on methanol and diesel fuel, significantly reducing GHG and harmful emissions such as SOx and NOx. Moreover, special materials prevent corrosion, and diesel cycle combustion in methanol mode and electronically controlled fuel injection are applied to enable stable high-power operation. An exhaust aftertreatment system (Selective Catalytic Reduction (SCR)) optimized for methanol engines has also been developed to meet the IMO's existing NOx emission regulations. As of October 2022, a total of 50 engines (for 13 vessels) have been ordered.

Figure 4-2 shows the fuel injection system of the HiMSEN H32DF-LM methanol dual-fuel engine. The electronic fuel pump replaces the mechanical fuel pump used in conventional medium-duty marine engines, enabling precise control of the timing and amount of fuel injection. The amount and timing of fuel injection for each cylinder can be adjusted independently. Furthermore, the integrated dual-fuel injection system efficiently integrates the diesel injection system of diesel mode, the pilot injection system used as an ignition source of methanol mode, and the methanol injection system, thereby simplifying the structure and improving maintainability.



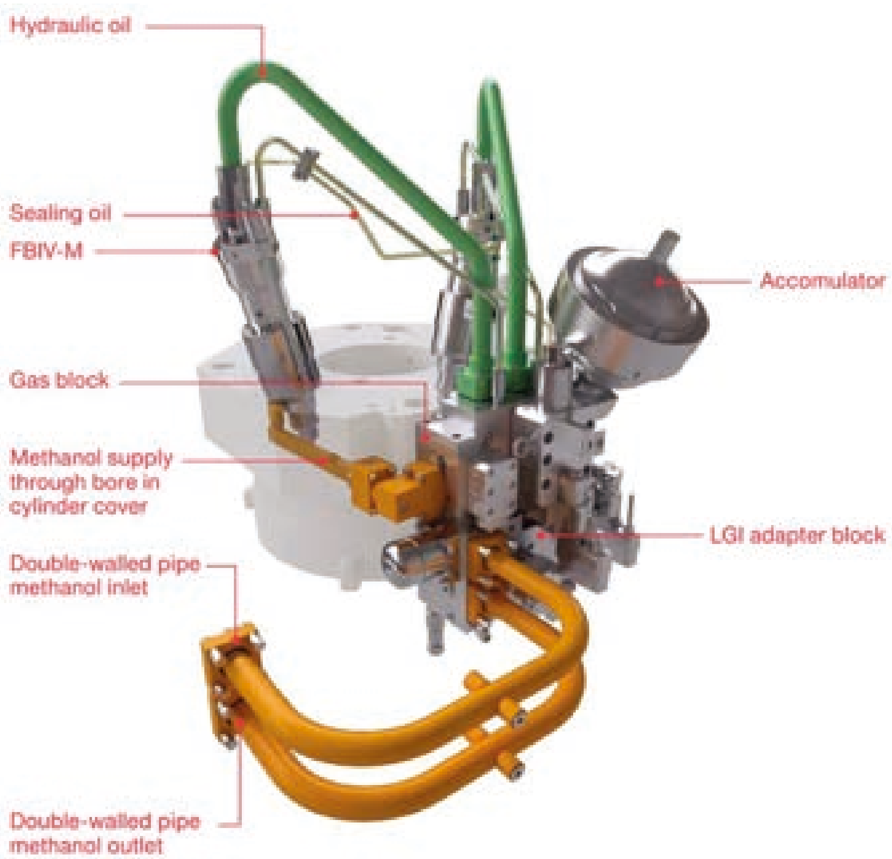
|Figure 4-2| Fuel injection system for HiMSEN H32DF-LM, a methanol dual-fuel medium-duty engine

- MAN ES (Energy Solutions)

The German engine manufacturer MAN Energy Solutions (MAN ES) has developed MAN B&W ME-LGIM, a two-stroke methanol engine, which was installed in seven 50,000 DWT tankers for Waterfront Shipping in 2016 [44]. The ME-LGIM engine is a dual-fuel engine that can run on methanol as well as HFO, MDO, and MGO. The demand for methanol engines is growing, with 110 ME-LGIM engines currently on order [45]. The ME-LGIM engine's performance has been proven based on more than 145,000 operating hours in methanol combustion mode. The company has also announced that it has received AIP certification for a four-stroke dual-fuel engine running on methanol in 2023 and will offer retrofit solutions for four-stroke methanol engines starting in 2024 [46-47].

The ME-LGIM engine requires pilot fuel in methanol combustion mode, and its amount corresponds to a maximum of 5% of the fuel consumption for full power in diesel combustion mode. Technically, the pilot fuel can be an eco-friendly fuel such as biofuel or e-diesel, in which case the engine can be carbon neutral. Based on engine combustion test results, the company has reported a reduction of about 30% in NOx emissions when switching from diesel to methanol combustion under the same operating parameters, due to the lower temperature of the methanol flame [48].

As a successor to the LGIM engine, the LGIM-W engine was also developed in which a methanol and water blending system was introduced. The addition of water to methanol reduces NOx emissions due to lower combustion temperatures, and it offers the economic advantage that an EGR or SCR system is no longer required if the NOx emission level meets the IMO's Tier III regulations. Tests by MAN ES have shown that using methanol blended with approximately 25-40% water and 5% pilot fuel (diesel) can reduce NOx emissions enough to reach Tier III emission levels [48].



|Figure 4-3| Components in the upper part of the cylinder in ME-LGIM engine [48]

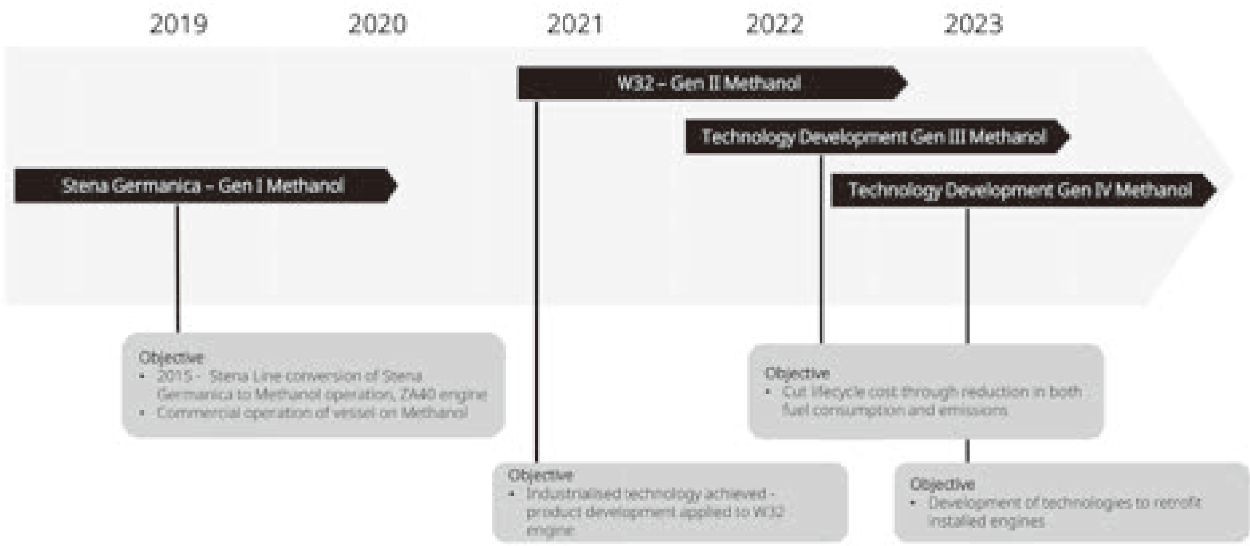
Figure 4-3 shows the main components in the upper part of the cylinder in the ME-LGIM engine. The operating concept of the engine includes the following functions [48]:

- Fuel Booster Injection Valves for Injection of Methanol (FBIV-M): An injector for injecting methanol into the combustion chamber. It combines a hydraulically operated plunger pump with an injection needle valve. As for the pump function, the FBIV uses hydraulic pressure to inject methanol by increasing pressure from a feed pressure of 13 bar to approximately 600 bar.
- Sealing Oil Supply Unit: A unit that supplies sealing oil to prevent methanol leakage from the operating parts of the methanol injection system.

- Double-walled Pipe: A pipe that safely distributes methanol to individual cylinders, with the second layer in the pipe covering all methanol piping inside the engine compartment. This outer pipe is vented to the outside atmosphere, eliminating the risk of methanol leaks in the engine compartment and allowing hydrocarbon (HC) sensors to detect leaks in the inner pipe.
- Engine Control System (ECS): A system that monitors methanol injection and combustion, and controls the engine to switch to diesel combustion mode under certain circumstances.
- Fuel Valve Train (FVT): A valve train that controls the flow of fluid between the fuel feed system and the engine.

- Wärtsilä

Finnish engine manufacturer Wärtsilä is offering technology to modify or replace existing engines to use methanol as a fuel. For ZA40S and W32 engines, the company already offers methanol propulsion technology, and it has announced that it will offer conversion technology for W20 engines in 2024 and W46F/FDF engines in 2025. It has also announced that more than 2,000 W32 engines currently in operation can be converted to methanol-fueled engines with no reduction in efficiency or power [49].



|Figure 4-4| Methanol engine development roadmap of Wärtsilä [50]

In 2015, Wärtsilä installed methanol dual-fuel engines on the 240-meter-long Stena Germancia ferry, which runs 14 hours between Germany and Sweden. Four ZA40 engines, medium-speed four-stroke engines in the 6,000 kW class, were modified to run on methanol. A high-pressure (600 bar) pump room was added, and a double-wall fuel pipe system was installed. Tests on the modified Z40S engines showed a 60% reduction in NOx emissions, 99% reduction in SOx emissions, and 90% reduction in particulate matter emissions [51-52].

In 2023, Wärtsilä developed the W32 Methanol engine, a four-stroke diesel engine that can use methanol as its fuel. The engine can also run on HFO, MDO, and liquid biofuels in addition to methanol, and can operate more efficiently and economically when using methanol, low-sulfur oil (<0.1%), and liquid biofuels. When methanol is used as the primary fuel instead of diesel, SOx emissions from combustion are reduced by 99%, NOx emissions by 60%, CO_2 emissions by 7%, and Filter Smoke Number (FSN), a measure of visible smoke and particle emissions, by 50%. With its NOx emission reduction performance, the W32 methanol engine can meet the IMO Tier II standards. When combined with SCR technologies such as NOx reduction agents, they can also meet the IMO Tier III standards. [53-54]

[Table 4-2] Wärtsilä W32 engine's key technical data [54-55]

Cylinder bore	320 mm	Piston stroke	400 mm
Cylinder output	580 kW/cyl	Piston displacement	32.2 L/cyl
Cylinder configuration	6, 7, 8 and 9 in-line	Mean effective pressure	28.9 bar
Speed	720, 750 rpm	Number of valves	2 inlet valves, 2 exhaust valves

- WinGD

Swiss engine manufacturer WinGD has announced that it will be possible to use methanol as a fuel starting in 2024 [56]. Furthermore, in 2022, the company began a joint development with South Korean engine manufacturer HSD Engine to accelerate the development of large methanol-fueled engines. The project's goal is to deliver a large engine that can run on green methanol by 2024, providing a power solution to shipowners to meet the IMO's 2050 target with the next generation of ships. In the joint development project, WinGD will oversee combustion and injection research, requirements of exhaust aftertreatment, and engine concept design, while HSD Engines will support cost-effective manufacturing and assembly, perform engine tests, and manufacture fuel feed and exhaust aftertreatment systems. The project is focused on the largest engines in WinGD's portfolio, the X92 and X82 engines, which the company says will be suitable for large and mega container ships [56-57].

WinGD announced that it will supply its 10X92DF-M methanol-fueled propulsion engines for four 16,000 TEU container ships for China's COSCO, with deliveries scheduled to begin in 2025. On the three ships that will be built first, X92-B engines will be installed and then converted to methanol engines before entering service, while the last ship will be equipped with methanol engines from the beginning. The X92DF-M engine is based on the widely used X92-B engine, which has long been used in container ships of shipping line companies, including COSCO Shipping Line, MSC, and CMA CGM. WinGD has announced that it will introduce a methanol conversion package for the X92-B engines upon delivery of the fourth ship under this contract, enabling ships with existing X92-B engines to be retrofitted to use methanol as a fuel [58].

- Japan

In Japan, six companies (Mitsui O.S.K. Lines, MOL Coastal Shipping, Tabuchi Kaiun, Niihama Kaiun, Murakami Hide Shipbuilding and Hanshin Diesel Works) announced that they have formed a strategic alliance to develop their own methanol-fueled propulsion vessel in order to promote the development of methanol-fueled ships and the decarbonization of ships. [59-60].

The developed vessel will be used for methanol transportation in Japan and is expected to be delivered in December 2024. Mitsui O.S.K. Lines (MOL), which currently operates four dual-fuel tankers with methanol-fueled propulsion capability, will be the owner of the vessel and will participate in development based on its experience with methanol-fueled ships. Tabuchi Kaiun and Niihama Kaiun will be responsible for the management of the vessel, while Murakami Hide Shipbuilding will build the vessel based on its experience in tanker construction. Based on its existing engine design, Hanshin Diesel Works will develop a low-speed, four-stroke diesel engine using methanol fuel.

4.2. Status of Methanol Fuel Tanks

- Characteristics of Methanol Fuel Tank

Methanol has a boiling point of 64.7°C at atmospheric pressure, making it highly volatile, but since it exists as a stable liquid at atmospheric temperature, there is no need to use low-temperature steel. However, it can be corrosive to some materials, so careful consideration must be given to material selection for tanks and pipes, seals, and other components.

The special paint applied to the cargo hold of a chemical tanker can be also applied to the methanol fuel tank, and the methanol fuel tank can be manufactured with the shipbuiliding steel (AH grade, A grade, etc.) generally applied to the hull structure. When coating the tank with zinc silicate, the outer structure and the inside of the tank must be made with flat surfaces, as flat surfaces without sharp edges are generally required. Care must be taken to avoid placing members inside the tank for the special coating, and it is important to note that outfitting for access to the cargo hold tank must be minimized.

Fuel tanks capable of storing methanol can also be used as tanks for conventional fuel, which means that conventional fuel can be used until the conversion to methanol takes place. To change fuel to methanol, the tank must be cleaned and the transfer pump must be replaced. The zinc silicate coating on the bottom of the tank may also require repair during the conversion if the bottom of the fuel tank is exposed to water [61]. Due to the hazardous properties of methanol to humans, a protective cofferdam is required around the methanol tank installed below the lowest water line, and methanol must remain inert at all times during operation. Methanol safety regulations are described in detail in Chapter 5.

Table 4-3 shows the storage characteristics of marine fuels. In the table, relative tank sizes are estimated based on a Handymax-class cargo ship with a cruising distance of 1,000 nm [64]. Methanol has a lower energy density than conventional fossil fuels (such as MGO) but a higher energy density than ammonia or hydrogen. The estimated storage tank size for methanol is larger than that for MGO, but is similar to that for LNG. Methanol tanks can be installed in areas of the ship where ammonia or LNG tanks could not be installed (e.g., below deck) due to fuel properties (such as pressure and toxicity) [62]. The firstly operating methanol-fueled ship, the Stena Germanica, had methanol fuel tanks installed by securing an empty space on the bottom of the ship [63]. Since the space at the bottom of the ship can be utilized for methanol fuel tanks, the overall space consumption on board can be reduced.

[Table 4-3] Characteristics of marine fuel storage [64]

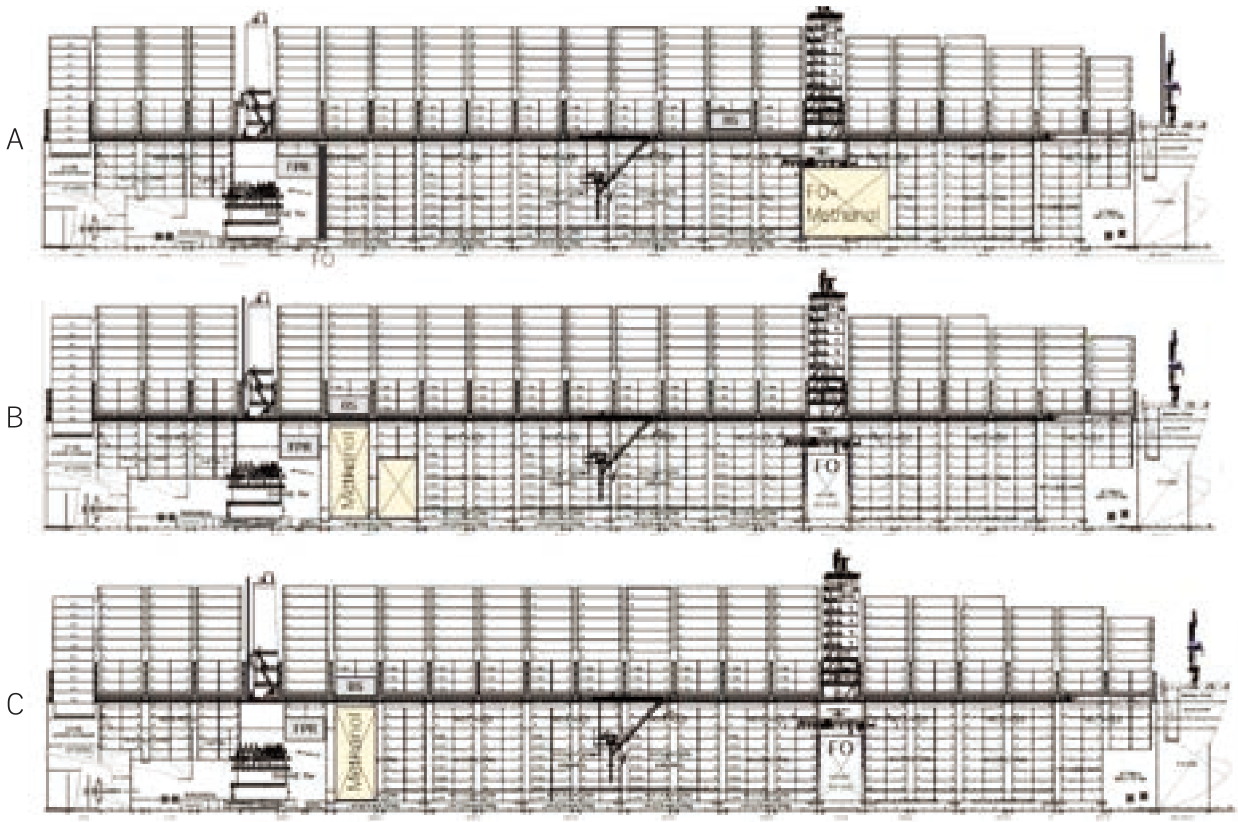
Fuel	LHV (MJ/kg)	Energy Density (GJ/m^3)	Storage Pressure (bar)	Storage Temperature (℃)	Relative size of Cargo Handling System (consideirng insulation)
MDO/MGO	42.7	36.6	1	20	1
LNG	55.6	25.0	1	-162	2.3
Methanol	19.9	15.8	1	20	2.3
Liquefied ammonia	18.6	12.7	1	-34	4.1
			10	20	
Liquefied hydrogen	120.0	8.5	1	-253	7.6

*Relative tank size is estimated based on a Handymax-class cargo ship with a cruising distance of 1,000 NM

- Cargo Loss when Converting to Methanol

Wärtsilä estimated that when including the ship's cofferdam, the size of space occupied for fuel storage in the ship would be 1.6 times larger for methanol compared to MGO [49]. A study evaluating the techno-economic feasibility of bulk carriers converted to green methanol-fueled ships found that more than 93% of the transportation tasks could be covered when a cargo capacity reduction of less than 3% was allowed [65]. In another study that performed LCA of ship fuels including methanol, ships using methanol as fuel showed a 4% reduction in cargo capacity compared to ships using HFO [17].

The Mærsk Mc-Kinney Møller Center (MMMC) published a project report on fuel conversion to methanol for a 15,000 TEU container ship [61]. The report proposes an arrangement and design of methanol fuel tanks, which changes depending on the preparation level for methanol conversion. It also describes that cargo loss varies depending on whether space is allocated for conversion and whether key structural elements and systems are in place.



|Figure 4-5| Arrangements of fuel tanks in a 15,000 TEU container ship for methanol conversion [61]

In Figure 4-5, A shows a fuel tank arrangement for a case where the level of preparation for methanol conversion is high, and B and C show fuel tank arrangements for cases where the level of preparation for methanol conversion is low. In A and B, the size of the methanol fuel tank is increased (16,000 m^3) to maintain the total energy of the fuel. In C, the size of the fuel tank is reduced (10,000 m^3) compared to A and B to minimize cargo losses. In the case of a high level of preparation for methanol conversion, such as A, some of the systems for methanol conversion are already in place, and an existing fuel oil tank can be used as a methanol tank. This can reduce cargo losses compared to installing an additional methanol tank later. When a section of the fuel oil tank is converted to a methanol tank, a small section of tank must exist to act as a buffer zone between the methanol and fuel oil. In the design of A, the methanol tank capacity is 16,000 m^3, and the cargo loss is about 240 TEU (1.5%).

If the ship's preparation level for methanol conversion is low and the fuel tank is not suitable for methanol storage, an additional tank should be arranged, as shown in B in Figure 4-5. In this case, the methanol tank capacity is the same as in case A, 16,000 m^3, but the cargo loss has increased to about 610 TEU. If a smaller methanol fuel tank of a 10,000 m^3 size is used to reduce the cargo loss, as shown in C in Figure 4-5, the space occupied by the fuel tank in the cargo hold is reduced, resulting in a cargo loss of about 400 TEUs. In other words, the cargo loss rate of container ships due to methanol conversion ranges from 1.5 to 4.0%, depending on the level of preparation.

4.3. Status of Methanol Fuel Supply Systems

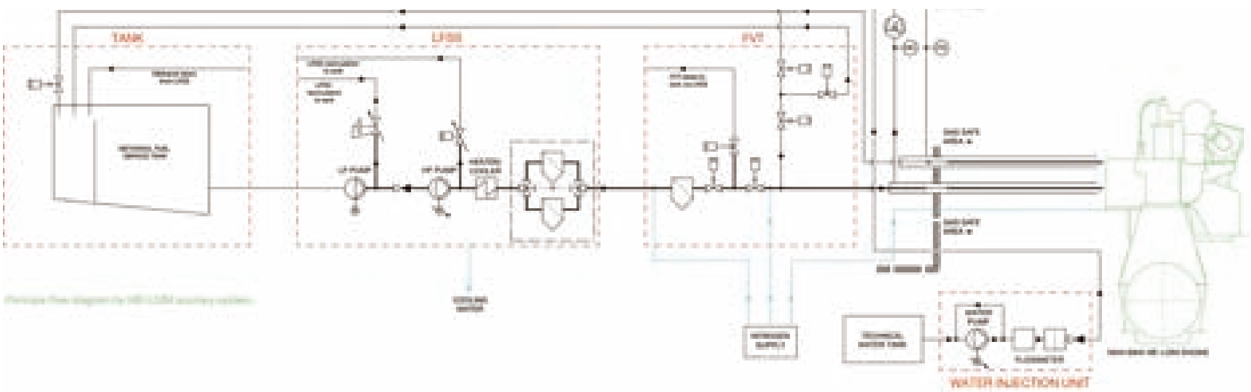
Because methanol has a very low viscosity compared to conventional HFO and diesel, there could be a higher risk of leaks. Furthermore, it must not leak to workers performing maintenance and repair. Therefore, methanol engines should have a double-walled fuel distribution system, and the fuel supply system should be designed with nitrogen purging so that the operators can work safely [66]. Other safety details for methanol are described in Chapter 5.

Methanol fuel supply systems can be divided into low-pressure methanol fuel supply systems and high-pressure methanol fuel supply systems based on the supply pressure. Low-pressure methanol fuel supply systems feed methanol at a pressure of approximately 10 to 13 bar and a temperature of 25 to 50°C, and are used by engine developers such as HD HHI, MAN ES, Anglo Belgian Corporation (ABC), and Caterpillar. When methanol is supplied to a MAN ES ME-LGIM engine at 10 bar, it is injected at 600 bar at the engine's fuel injection valve, the FBIV [48]. On the other hand, Wärtsilä uses a high-pressure methanol fuel supply system for its W32 methanol engine to feed methanol: the fuel supply system feeds methanol compressed at about 400 bar to the engine [39].

- Low-pressure Methanol Fuel Supply System

The ME-LGIM engine from MAN ES is an example of a low-pressure methanol fuel supply system. It uses temperature-controlled methanol at a constant feed pressure, with the feed flow rate varying according to engine load. Low-flashpoint fuel supply systems (LFSS) must supply methanol to the engine while complying with requirements related to temperature, flow rate, pressure, and performance. The methanol LFSS from MAN ES is designed based on the same concept as conventional fuel oil supply systems, and Figure 4-6 shows its disclosed process diagram. Fuel is drawn from a service tank containing methanol in liquid form and pressurized by low pressure (LP) and high pressure (HP) pumps to a feed pressure of approximately 13 bar. It must be guaranteed that the fuel remains in the liquid state at the feed pressure and that cavitation does not occur at the temperatures it is exposed to before being injected into the FBIV. A heater/cooler is placed in the fuel supply system to maintain the proper fuel supply temperature [48].

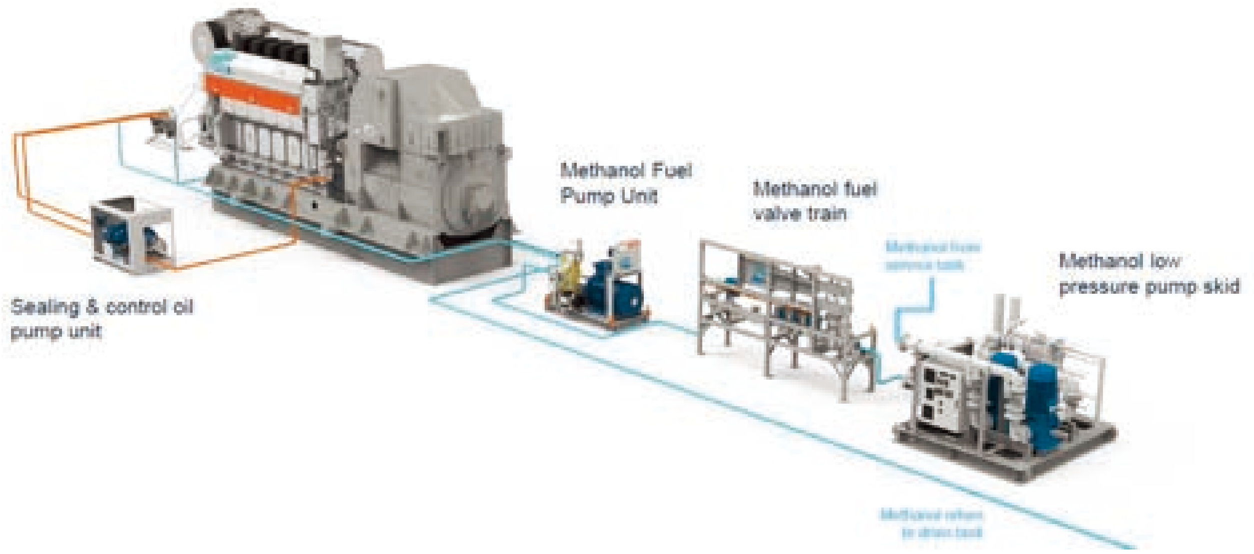
- Methanol fuel service tank: Methanol is stored in the service tank at normal pressure. The interior of the methanol fuel service tank is divided into two compartments, one to hold the methanol being vented/purged and the other for fuel supply, separated by a partition of a certain height.
- Fuel Valve Train (FVT): The FVT connects the fuel supply system to the engine through a master fuel valve (MFV) and is also connected to the nitrous injection unit to purge inside the pipe. The water injection system used to reduce NOx emissions is also connected to the FVT. The valve train is placed with the fuel supply system in a ventilated room and delivers fuel to the engine through double-walled pipe.
- Purge/Return System: Due to the low flash point of methanol, there are several operating scenarios where the fuel pipe must be emptied and deactivated. For the ME-LGI engine series, the fuel pipes in the engine and engine room are arranged to allow liquid fuel to be purged, and the purged fuel is returned to the service tank. After the methanol fuel is returned to the service tank, a complete purging and inerting of the double-walled pipe system is performed. Furthermore, as part of the engine start-up procedure, the entire methanol fuel supply system, including the FVT, is filled with nitrogen and checked for pressure maintenance.
- Water Injection System: The water injection system supplies water to be mixed with methanol to reduce NOx emissions to meet Tier III levels. It consists of a pump, filter, and pressure transmitter. Since the water and methanol are delivered to be mixed through the FVT, water blending is controlled by the Engine Control System (ECS). The water injection system is designed to be placed in a gas safe area such as the engine room.



|Figure 4-6| Process diagram of the low-pressure methanol fuel supply system for MAN ES ME-LGIM engine [48]

- High-pressure Methanol Fuel Supply System

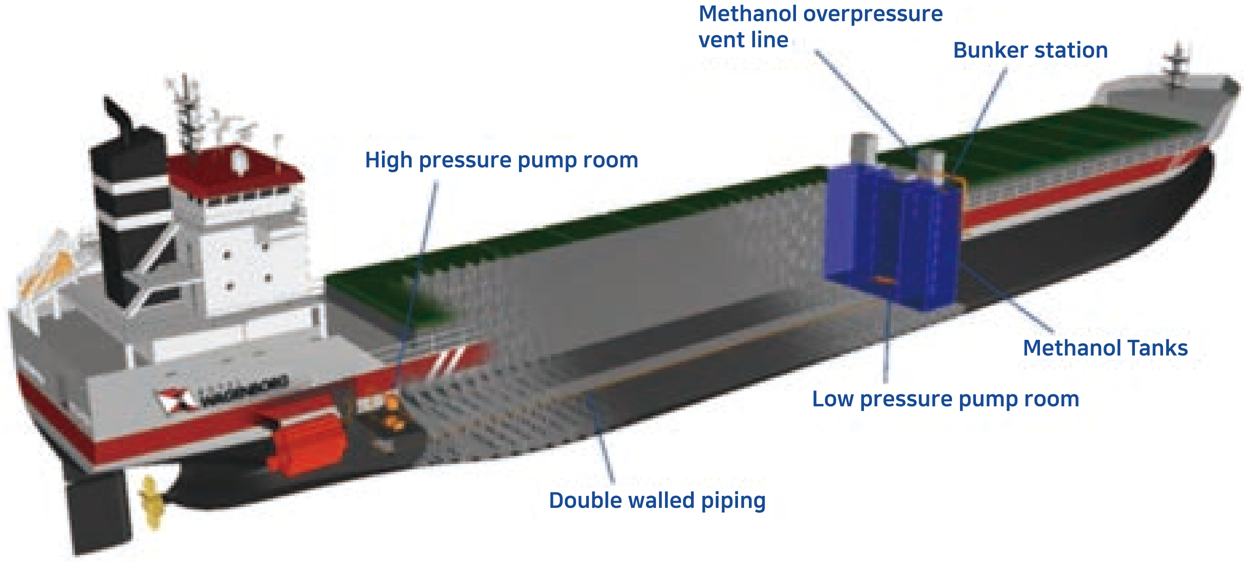
The W32 methanol engine from Wärtsilä is an example of a high-pressure methanol fuel supply system. A methanol fuel supply system consists of a methanol low-pressure pump, a methanol FVT and a methanol high-pressure pump unit. The methanol low-pressure pump supplies methanol from the service tank to the FVT, and a single unit can be used for all engines on the vessel. It consists of two low-pressure pumps and a cooler, connected to a recirculation line to prevent excessive flow rate. The methanol FVT is also a single unit, which can be used for all engines, and ensures that the fuel passed through the double filter is safely supplied to the high-pressure methanol pump unit. Each line from the FVT to the methanol pump unit is equipped with a master fuel valve, flow meter, and pressure gauge. The methanol high-pressure pump units, which are connected one-to-one to the engines, are multi-stage piston pump units and are installed outside the engine room. It can supply methanol at pressures up to 600 bar and includes a leakage recovery system and the lubricating oil cooling function [49-50].



|Figure 4-7| High-pressure methanol fuel supply system for Wärtsilä W32 methanol engine [49]

lubricating oil coming from the engine lubrication system and supplies the sealing oil and control oil needed for the engine to operate properly. Sealing oil performs the sealing function at the injector nozzles to prevent methanol from leaking into the engine room, and control oil performs the engine's control function. Sealing oil and control oil are supplied at up to 700 bar and 400 bar, respectively. The sealing and control oil pump unit also performs a cooling function to prevent the temperature of the methanol in the engine from rising too high, and a control function to prevent methanol from flowing during emergency shutdowns and maintenance [49-50].

As part of the Green Maritime Methanol consortium project, Marine Service Noord, a marine system design and equipment supplier, conducted a case study to convert the cargo ship MV Eemsborg into a methanol-fueled propulsion vessel [67]. The MV Eemsborg, shown in Figure 4-8, is an 11,300 DWT cargo ship, which has a Wärtsilä 9L32C engine with a power output of 4,500 kW as its main engine. Converted into a methanol-fueled propulsion vessel, the MV Eemsborg's low-pressure pump room is connected by double-walled piping to the high-pressure pump room located next to the engine room. The high-pressure pump room contains a buffer tank and high-pressure pumps. The high-pressure pumps compress the methanol to a pressure of 450 bar before it is fed to the engine. The methanol in the methanol return line is circulated to the buffer tank. By using a buffer tank to add water to the methanol fuel, Tier III regulation can be complied with, without the use of SCR equipment. Nitrogen is used for inerting of methanol tanks and the space between the inner and outer pipes of double-walled piping [68].



|Figure 4-8| Conceptual drawing of the MV Eemsborg, a cargo vessel converted to use methanol as fuel [67]

4.4. Status of Methanol-fueled Ship Orders

Clarksons Research Services (CRS) analyzed ships ordered in 2022 and found that 61% of new-build tonnage ordered (35% by number) will use alternative fuels. Over half of the tonnage ordered (397 orders, 36.7 million GT) were LNG dual-fuel vessels, while 43 methanol-fueled vessels were ordered with a total of 5 million GT, accounting for 7% of the tonnage ordered. In addition, LPG-powered vessels accounted for 1.1% with 17 orders totaling 800,000 GT, and battery hybrid vessels accounted for 1.2%. Furthermore, there were some orders for alternative fuel-ready vessels, which are designed to make the conversion into alternative fuel-powered vessels relatively easy. 90 ammonia-ready ships were ordered, accounting for 10.8% of the tonnage ordered, while 31 LNG-ready ships and 22 methanol-ready ships were ordered [69].

- A.P. Møller - Maersk

The Danish shipping company A.P. Møller - Maersk has set a goal of decarbonization by 2040, and has also set a short-term goal of reducing GHG emissions by 50% in 2030 compared to the level in 2020 by ordering only ships that can run with alternative fuels [70]. In line with this goal, in June 2021, the company ordered a small 2,100 TEU methanol-fueled containership from Hyundai Mipo Dockyard and took delivery of the ship in July 2023 [71]. In August 2021, the company ordered eight large 16,000 TEU methanol-fueled containerships from HD Hyundai Heavy Industries, which are planned to be delivered in the first quarter of 2024. In January 2022, the option for four additional ships was exercised on the existing contract, and the ships will be delivered in 2025 [72]. In October 2022, a new order was placed with HD Hyundai Heavy Industries for six large 17,000 TEU methanol-fueled containerships, which are planned to be delivered in 2025 [70]. In June 2023, the company ordered six 9,000 TEU medium-sized methanol-fueled containerships from China's Yangtze River Shipbuilding Co. Ltd., which are planned to be delivered between 2026 and March 2027 [73]. Maersk's total order recorded 25 methanol-fueled containerships, of which one has been delivered.

- CMA CGM

In June 2022, French shipping company CMA CGM ordered six 15,000 TEU methanol-fueled containerships from the Dalian Shipbuilding Industry Company (DSIC) Group, part of China State Shipbuilding Corporation (CSSC), as part of its efforts to achieve carbon neutrality by 2050, with delivery scheduled for 2025 [74]. In February 2023, the company ordered twelve 13,000 TEU methanol-fueled containerships from Hyundai Samho Heavy Industries for delivery in 2026 [75]. In April 2023, the company ordered six additional 15,000 TEU methanol-fueled containerships from CSSC for delivery between 2025 and 2026 [76]. In other words, CMA CGM ordered 24 methanol-fueled containerships in total [77].

- COSCO

In October 2022, Chinese state-owned shipping company COSCO placed an order for 12 extra-large 24,000 TEU methanol-fueled containerships. Among the 12 ships, seven ships will be delivered to Hong Kong's Orient Overseas Container Line (OOCL) and five to COSCO Shipping Lines. Nantong Cosco KHI Ship Engineering (NACKS) and Dalian Cosco KHI Ship Engineering (DACKS), a joint venture of COSCO and Japan's Kawasaki Heavy Industries, will build ships and deliver them between the third quarter of 2026 and the third quarter of 2028 [78]. Additionally, in April 2023, the company ordered three 16,000 TEU methanol-ready containerships and one methanol-fueled containership. The four ships will be built at the company's partner shipyard in Yangzhou and are expected to be delivered in the second half of 2025 [79].

- HMM

them, seven ships will be built by Hyundai Samho Heavy Industries and two by HJ Shipbuilding & Construction Company, and will be delivered to HMM in 2025 for deployment on routes between South America and India. The nine ships will be equipped with MAN B&W G80ME-LGIM dual-fuel engines and exhaust gas recirculation (EGR) systems from MAN ES.

- Evergreen Marine

The Taiwanese shipping company Evergreen Marine placed an order for twenty-four 16,000 TEU methanol-fueled containerships in July 2023. Among them, sixteen ships will be built by Samsung Heavy Industries and eight by Japan's Nihon Shipyard Co. for delivery from 2026 [81].

[Table 4-4] Status of methanol fuel-powered containership orders per shipping company

A.P. Møller - Maersk	Completed delivery of one 2,100 TEU (Hyundai Mipo Dockyard) Ordered twelve 16,000 TEU (HD Hyundai Heavy Industries), six 17,000 TEU (HD Hyundai Heavy Industries), and six 9,000 TEU (Yangtze River Shipbuilding Co. Ltd.)
CMA CGM	Ordered twelve 15,000 TEU (CSSC), and twelve 13,000 TEU (Hyundai Samho Heavy Industries)
COSCO	Twelve 24,000 TEU (NACKS, DACKS), and four 16,000 TEU (COSCO)
HMM	Nine 9,000 TEU (Hyundai Samho Heavy Industries, HJ Shipbuilding & Construction Company)
Evergreen Marine	Twenty-four 16,000 TEU (Samsung Heavy Industries, Nihon Shipyard)

05

Safety on Methanol-fueled Ships

5.1. Risk factors of methanol

- Summary of risk factors, prevention, and response

Methanol is a light, colorless, volatile, and highly flammable liquid and vapor with high fire risks (level 3) and a moderate health hazard (level 2) based on the US National Fire Protection Association (NFPA)'s standard. It is toxic when absorbed into the body through ingestion, inhalation, and skin contact, causing optic neuropathy, hepatotoxicity, nephrotoxicity, and central nervous system and reproductive dysfunction effects [82]. As it is a highly flammable liquid and vapor, it has a high possibility of fire and explosion, and can cause corrosion.

To prevent accidents, it should be isolated from heat sources and ignition sources, and storage containers should be tightly sealed. The storage container must be electrically grounded, and equipped with explosion-proof equipment, ventilation and exhaust systems, and spark-proof equipment; anti-static measures are also required. Methanol vapor should not be inhaled, and should not be ingested, drunk, or smoked when handling. It should be used outdoors or in an area with ventilation systems, and personal protective equipment should be worn if direct contact is required. If swallowed, one should wash mouth and seek immediate medical attention; if it is in contact with skin or hair, one should immediately take off all contaminated clothing and flush the skin with water. Contaminated clothing should be washed before reuse. When inhaled while washing, one should move to a place with fresh air and take a rest. Fomepizole (or 4-methylpyrazole) is available for the treatment of methanol poisoning and is listed on the WHO Essential Medicines List. The information on main hazards and prevention, and response can be found in Table 5-1.

[Table 5-1] Methanol risks and hazards, prevention and response information

Hazards	• Highly flammable liquids and vapors (H225) • Toxic if ingested (H301) • Toxic in contact with skin (H311) • Toxic if inhaled (H331) • Single oral or skin contact exposure may cause damage to certain organs (e.g., liver, kidney, central nervous system, and optic nerve) (H370)
Exposure symptoms	• Abdominal pain, vomiting, difficulty breathing, and unconsciousness if ingested • Dry skin, rash, erythema, and dermatitis if absorbed into the skin • Cold symptoms, dizziness, headache, vomiting, and nausea if inhaled • Eye redness, pain, inflammation, tearing

Prevention	• Keep away from heat, hot surfaces, sparks, flames, and other sources of ignition (P210) • Storage containers must be tightly sealed (P233) • Storage containers must be grounded (P240) • Explosion-proof equipment and ventilation and exhaust systems are required (P241) • Spark-proof equipment must be used (P242) • Anti-static measures are required (P243) • Mists, gases, vapors, and sprays must not be inhaled (P260) • Thoroughly wash exposed skin after handling (P264) • Do not eat, drink, or smoke when handling (P270) • It should be handled outdoors or in an area with ventilation systems (P271) • Wear personal protective equipment such as an air-supplied respirator, protective goggles, chemical-resistant gloves, and protective clothing if direct contact is required (P280).
Response	• If swallowed, wash mouth and seek immediate medical attention (P301+P310, P330) • In case of contact with skin or hair, immediately take off all contaminated clothing and wash skin with water (P303+P361+P353) • In case of inhalation, move to a place with fresh air to rest (P304+P340). • Contaminated clothing should be washed before reuse (P363) • In case of fire, use a carbon dioxide, powder, or alcohol-resistant foam fire extinguisher to extinguish the fire (P370+P378).
Storage and disposal	• Store in a well-ventilated area and keep at a low temperature (P403+P235) • Store under lock and key (P405) • In case of disposal, do not dispose of down the drain, but dispose of contents and containers in accordance with waste legislation. (P501)

- Toxicity

Direct contact with methanol can cause serious toxic effects in humans. Methanol can be absorbed into the body through all kinds of routes such as ingestion, inhalation, and skin contact, and once absorbed, methanol is oxidized and changed to formaldehyde, which becomes formic acid by alcohol dehydrogenase, and is finally oxidized and decomposed to water and carbon dioxide. However, the decomposition rate of methanol is very slow, leading to the accumulation of toxic substances such as formaldehyde and formic acid in the body, and consequently damage to the human body. Formaldehyde is distributed to various tissues of the body, including cerebrospinal fluid, blood, and urine, and is especially damaging when it is absorbed into the ocular and vitreous humor liquid. It causes atrophy of the optic nerve and retina, leading to blindness.

The incomplete combustion of methanol can also form formaldehyde. This can indirectly damage the human body and cause secondary environmental pollution. Depending on the manufacturing specifications and operating conditions, it has been reported that the combustion exhaust of methanol engines can contain formaldehyde at five times the level of conventional engines [83]. However, it has also been reported that the formaldehyde production reaction is inhibited when combustion occurs under high pressure and high-temperature conditions (higher than 1,300℃) [28, 84].

According to the standard of the National Institute for Occupational Safety & Health (USA NIOSH), the Time Weighted Average (TWA) exposure limit for methanol is 200 ppm and the Short Term Exposure Limit (STEL) is 250 ppm for a one-day work period. The reported toxicity data can be found in Table 5-2.

[Table 5-2] Methanol toxicity data

LD50/LC50(Fatality 50%)	
LD50 (Oral, rat)	1187-2769 mg/kg weight (BASF test)
LD50 (Dermal, rabit)	17100 mg/kg (Insufficient data)
LC50 (Inhalation, rat)	128.2 mg/l air (BASF test, 4h, Vapor)
Acute Toxicity Estimate (ATE)	
ATE US (Oral)	100 mg/kg Weight
ATE US (Dermal)	300 mg/kg Weight
ATE US (Inhalation - gas)	700 ppmV/4h
ATE US (Inhalation - vapor)	3 mg/L/4h
ATE US (Inhalation - dust or mist)	0.5 mg/L/4h
Exposure standard	
Korean Ministry of Employment and Labor (ppm)	200, 250 (STEL)
USA OSHA (ppm)	200
USA NIOSH (ppm)	200, 250 (STEL)

- Low flash point, fire, and explosion

The flash point of methanol is reported to be around 10-12℃ below atmospheric temperature. This indicates that a leak can lead to the possibility of ignition at atmospheric temperature, implying that it has the potential to cause a fire or explosion without separate heat sources in case of the existence of an ignition source. Combustion of conventional fuels results in a visible flame, whereas high concentrations of methanol are characterized by a flame invisible during daylight hours [85]. Consequently, the possibility of secondary damage from fire is high and there should be consideration of fire detection methods. There is a risk of explosion when reacting with oxidizing agents. The lower explosion limit (LEL) is 6.0%.

- Viscosity, corrosion and, and swelling

Methanol has a lower viscosity than conventional HFO or diesel oil, which can lead to more frequent leaks. This means that conventional fuel oil leak seal methods may be insufficient [86].

Methanol has a strong corrosion-inducing effect and is also known to cause swelling on plastic and rubber surfaces. This is also likely to cause problems for equipment with plastic or rubber components inside, such as valves and pumps [87].

5.2. Risk Assessment

- Definition of risk and considerations for ships using low-flashpoint fuels

Risk is a combination of the probability of an event occurrence (frequency) and the severity of its consequences (consequence), usually expressed in the form of a product. KR (Korean Register of Shipping) describes recommended methods and cases for risk assessment of ships using low-flashpoint fuels in "Appendix 3: Risk Assessment" in KR Rules for Ships Using Low-flashpoint Fuels and Paragraph 103 describes the following items that can be considered in risk assessment for ships using low-flashpoint fuels.

(1) Equipment installed on board to receive and store fuel, control the condition, and transfer it to more than one main engine, boiler, or other fuel-consumption system, as necessary: Bunkering manifolds, valves, piping, tanks, pumps/compressors, heat exchangers and instruments.

(2) Equipment that controls operation: Pressure and temperature controllers and monitoring devices, flow regulators, signal processors, and control panels.

(3) Equipment that generates detection, alarms, and safety measures: Detectors that identify fuel leaks and fires caused by leaks, and that shut off the fuel supply to fuel-consumption systems.

(4) Equipment that vents, receives, or treats unintended fuel: Venting pipes, masts, and valves, overflow tanks, secondary containment, and ventilation devices.

(5) Fire extinguishers and arrangements to protect hull surfaces from the fire, fuel contact, and spread of fire: Water sprays, water curtains, or fire dampers.

(6) Systems for purging or inerting fuel lines: Nitrogen storage and supply devices for purging/inerting bunkering systems and devices used for transfer/disposal of fuel

(7) Systems and structures receiving devices: Fuel storage area, tank connection area, and fuel storage areas

- Information from the risk assessment

Paragraph 104 of Appendix 3: Risk Assessment KR Rules for Ships Using Low-flashpoint Fuels specifies that risk assessment techniques and criteria do not necessarily require quantitative measurements, but must be of a sufficient level of assessment contributing to the confirmation of whether measures to eliminate the risk are necessary or adequately reduced. The minimum information by the risk assessment is as follows.

(1) Risk factor identification: Potential contributors to damage by low-flashpoint fuel. Systematic identification of undesirable events leading to serious injury or death, environmental pollution, and/or loss of structural strength or integrity of the ship.
(2) Consequence analysis: The potential severity of risk factors. The potential severity (i.e., consequences) related to serious injury, single or multiple fatalities, harmful environmental impacts, and significant structural damage/ship damage that endanger safe operations.
(3) Probability analysis: the probability or frequency of risk factors to be occurred.
(4) Risk analysis: Risk can be defined as consequence severity X occurrence frequency.
(5) Risk assessment: A judgment about the acceptability of the risk. The risk should be compared with the criteria to determine whether the risk has been adequately reduced. Recognized techniques can be referred to from ISO 31010, ISO 17776, ISO 16901, NORSOK Z-013, CPR 12E or CCPS, and HSE. If the risk assessment results in an unacceptable rating, risk reduction measures must be provided; in case of a manageable rating, they may be considered and implemented if practical and cost-effective.

- Considerations for risk reduction measures

Appendix 3: Risk Assessment in KR Rules for Ships Using Low-flashpoint indicates that the following considerations should be made for risk reduction measures.

(1) Consideration of the As Low As Reasonably Practicable (ALARP) principle: Risk reduction measures should be implemented to the extent that the cost of implementing the measures is reasonably practicable.
(2) When considering reduction measures, the following hierarchy for reduction is recommended.
    (A) Measures to prevent undesirable events: Reduce the likelihood of an undesirable event so that it does not happen.
    (B) Measures to prevent harm in case of undesirable event: Reduce the severity of the consequences after an undesirable event occurs.
(3) When considering reduction measures for an inherently safer design, it is better to consider technical solutions rather than procedural controls, and passive measures rather than active measures.
(4) To determine if a reduction measure is effective, it is useful to describe or diagrammatize the path from cause to consequence, and review the effectiveness of the measure.
(5) If it is difficult for the subject matter expert to judge whether it is practical and cost-effective, a cost-benefit analysis is possible to be applied. If the reduction measures are not implemented,

despite the fact that the expert determined it as practical and cost-effective, a documented justification should be provided.

- Risk assessment requirements for methanol-fueled ships

Section 3 of "Appendix 5: Requirement for Ships Using Methyl/Ethyl Alcohol As Fuel" in the KR Rules for Ships Using Low-flashpoint Fuels describes requirements for the risk assessment (302) of methanol-fueled ships as shown in Table 5-3.

[Table 5-3] 302. Risk assessment requirements of Appendix 5, for ships using methyl/ethyl alcohol as fuel

Section 3 General Requirement

302. Risk Assessment

1. The risk assessment should be performed to ensure that the risks from the fuel use are handled in terms of their impacts on persons on board, the environment, and the structural strength or integrity of the ship. The risk factors related to the physical arrangement, operation, and maintenance of the ship according to reasonably foreseeable failure, should be considered.
2. The risk assessment required by Paragraph 1 for fuel-powered ships should include, but not be limited to, the following items.
   (1) Paragraph 2 of 510.
   (2) Item (1) of Paragraph 1 of 803.
   (3) Paragraph 2 of 903.
   (4) Item (8) of Paragraph 1 of 1507.
3. The risk should be interpreted via an acceptable and recognized risk analysis technique, while considering the loss of function, damage to components, fire, explosion, and electrical shock at least. The analysis should be performed to eliminate risks wherever possible. Risks that cannot be eliminated, should be minimized to the extent necessary.
4. The details of the risks and the reduction measures should be documented to satisfy our ship classification in accordance with the corresponding requirements of the Risk Based Ship Design Approval Guidelines.

In particular, the details of the specified items to be included in Paragraph 2 are as follows.

- Paragraph 2 of 510. (Drip tray): Each drip tray should have enough capacity to handle the maximum outflow based on the risk assessment.
- Item (1) of Paragraph 1 of 803. (Provisions for bunkering station): Bunkering stations should be located on open decks with sufficient natural ventilation. Enclosed or semi-enclosed bunkering stations should be specially considered in the risk assessment.
- Paragraph 2 of 903. (General provisions for fuel supply system): Safe access means for the operation and inspection of fuel supply systems should be provided and arranged so that the con-

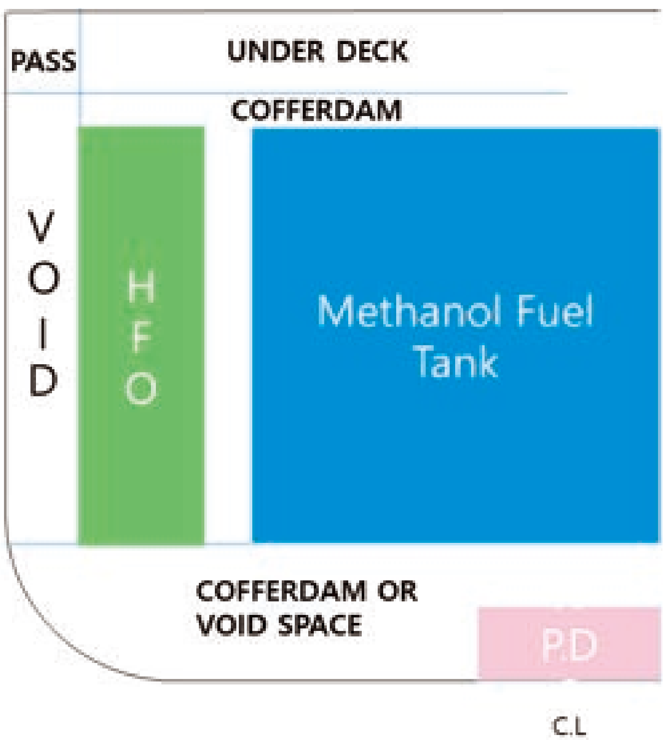
sequences of fuel leakage can be minimized. The causes and consequences of fuel leakage should be considered through the risk assessment of 302.

- Item (8) of Paragraph 1 of 1507. (Fuel vapor detection): All ventilation openings in living quarters and machinery space, if required as a result of the risk assessment defined in 302.

5.3. Safety Regulations and Training

- The highlight of safety regulations

Since the safety regulations for methanol-fueled ships are based on the IGF Code, there are parts corresponding to the safety regulations required for LNG carriers and LNG-fueled ships. However, as methanol has different characteristics (e.g., toxicity) from LNG, clear differences also exist in the safety regulations. Since methanol exists as a liquid at atmospheric temperature and pressure, no particular measures are required to keep it low-temperature during storage. Thus, a secondary barrier designed to prevent brittle fracture is not required. As a result, unlike LNG or ammonia fuel tanks, methanol tanks can be deployed as integral fuel tanks where part of the hull structure belongs to the tank, but the fuel tank must be isolated by a cofferdam.



|Figure 5-1| Example of methanol fuel tank arrangement

The following are the main features defined by the IMO's Interim Guidelines for the Safety of Ships Using Methyl/Ethyl Alcohol as Fuel (MSC.1/Circular.1621), and Appendix 5: Requirement for Ships Using Methyl/Ethyl Alcohol As Fuel in KR Rules for Ships Using Low-flashpoint Fuels.

[Table 5-4] Key features of safety regulation requirements for methanol-fueled ships

Functional requirements for ship design and arrangement (502)	•Fuel containment systems, fuel piping and other fuel release sources should be located and arranged such that released fuel is led to safe locations. (502.2.) •Access or other openings to spaces containing potential sources of fuel release should be arranged such that flammable, asphyxiating or toxic vapours or liquids cannot escape to spaces that are not designed for the presence of such substances (502.3.) •Probability of a fire or explosion in a machinery space as a result of a fuel release should be minimized in the design, with special attention to the risk of leakage from pumps, valves and connections (502.4.)
General provisions for arrangement (503)	•Tanks containing fuel should not be located within accommodation spaces or machinery spaces of category A. (503.1.) •Integral fuel tanks should be surrounded by protective cofferdams, except on those surfaces bound by shell plating below the lowest possible waterline, other fuel tanks containing methyl/ethyl alcohol, or fuel preparation space. (503.2.) •The fuel containment system should be abaft of the collision bulkhead and forward of the aft peak bulkhead. (503.3.) •Fuel tanks on open decks should be surrounded by coamings and spills should be collected in a dedicated holding tank. (503.5.)
Independent fuel tanks (504)	•Independent tanks may be accepted on open decks or in a fuel storage hold space (504.1.) •Independent fuel tanks should be fit with mechanically protection, and drip tray arrangements if located on an open deck. (504.2.) •Independent fuel tanks should be secured to the ship's structure. The arrangement for supporting and fixing the tanks should be designed for the maximum expected static, dynamic inclinations and accidental loads as well as the maximum expected values of acceleration, taking into account the ship characteristics and the position of the tanks (504.3.)
Portable fuel tanks (505)	•Portable fuel tanks should be located in dedicated areas fitted with mechanical protection and drip trays if located on an open deck. (505.1.) •Portable fuel tanks should be secured to the deck while connected to the ship systems. The arrangement should be designed for the maximum expected static and dynamic inclinations, as well as the maximum expected values of acceleration (505.2.) •Consideration should be given to the ship's strength and the effect of the portable fuel tanks on the ship's stability (505.3.)

	•Connections to the ship's fuel piping systems should be made by means of approved flexible hoses suitable for methyl/ethyl alcohol. (505.4.) •Arrangements should be provided to limit the quantity of fuel spilled in case of inadvertent disconnection or rupture of the non-permanent connections. (505.5.) •Control, monitoring and safety systems for portable fuel tanks should be integrated in the ship's control, monitoring and safety systems. (505.7.) •When connected to the ship's fuel piping system, each portable tank should be capable of being isolated at any time and isolation of one tank should not impair the availability of the remaining portable tanks. (505.9.)
Location and protection of fuel piping (507)	•Fuel piping should be located less than 800 mm away from the ship's side. (507.1.) •Fuel piping should not be led directly through accommodation spaces, service spaces, electrical equipment rooms or control stations. (507.2.) •Fuel piping that passes through enclosed spaces in the ship should be enclosed in a pipe or duct that is gas and liquid tight towards the surrounding spaces with the fuel contained in the inner pipe. All fuel pipes should be self-draining to suitable fuel or collecting tanks in normal condition of trim and list of the ship. (507.4.)
Bilge systems (509)	•Bilge systems installed in areas where fuels to which this appendix applies can be present should be segregated from the bilge system of spaces where the fuels cannot be present. (509.1.) •One or more holding tanks for collecting drainage and any possible leakage from fuel pumps, valves or double walled inner pipes located in enclosed spaces should be provided. Means should be provided for safely transferring contaminated liquids to onshore reception facilities. (509.2.) •The bilge system serving the fuel preparation space should be operable from outside the fuel preparation space. (509.3.)
Drip trays (510)	•Drip trays should be fitted where leakage and spill may occur (510.1.) •Each tray should have a sufficient capacity to ensure that the maximum amount of spill according to the risk assessment can be handled. (510.2.) •Each tray should be provided with means to safely drain spills or transfer spills to a dedicated holding tank, preventing backflow from the tank. (510.3.) •The holding tank should be equipped with a level indicator and alarm, and should be inerted at all times during normal operation. (510.5.)
Arrangement of entrances and other openings in enclosed spaces (511)	•For safe access, horizontal hatches/openings to fuel tanks or cofferdams should have a minimum clear opening of 600x600 mm that facilitates the hoisting of an injured person from the bottom of the tank/cofferdam. For access through vertical openings providing main passage through the length and breadth within fuel tanks and cofferdams, the minimum clear opening should not be less than 600x800 mm at a height of not more than 600 mm from bottom plating unless gratings or footholds are provided (511.6.)

Fuel tank venting and gas freeing system (603)	•The fuel tanks should be fitted with a controlled tank venting system. (603.1.) •A fixed piping system should be arranged to enable each fuel tank to be safely gas freed, and to be safely filled with fuel from a gas-free condition. (603.2.) •The formation of gas pockets during the gas freeing operation should be avoided by considering the arrangement of internal tank structure and location of gas freeing inlets and outlets. (603.3.) •Pressure and vacuum relief valves should be fitted to each fuel tank to limit the pressure or vacuum in the fuel tank. Design and arrangement should prevent flame propagation into the fuel containment system. (603.4.) •The fuel tank-controlled venting system should be designed with redundancy for the relief of full flow overpressure and/or vacuum. (603.6.). •The fuel tank vent system should be sized to permit bunkering at a design loading rate without over-pressurizing the fuel tank. (603.8.) •The fuel tank vent system should be sized to permit bunkering at a design loading rate without over-pressurizing the fuel tank. (603.9.)
Inerting and atmospheric control within the fuel storage system (604)	•All fuel tanks should be inerted at all times during normal operation. (604.1.) •Cofferdams should be arranged either for purging or filling with water through a non-permanent connection. Emptying the cofferdams should be done by a separate drainage system, e.g. bilge ejector. (604.2.) •The system should be designed to eliminate the possibility of a flammable mixture atmosphere existing in the fuel tank by utilizing an inerting medium. (604.3.) •To prevent the return of flammable liquid/vapour to the inert gas system, the inert gas supply line should be fitted with two shutoff valves in series with a venting valve in between. In addition, a closable non-return valve should be installed between the double block and bleed arrangement and the fuel system. (604.4.) •Blanking arrangements should be fitted in the inert gas line to individual tanks. (604.6.) •Fuel tank vent outlets should be situated normally not less than 3 m above the deck. The vent outlets are also to be arranged at a distance of at least 10 m from the nearest air intake or opening to accommodation and service spaces and ignition sources. The vapour discharge should be directed upwards in the form of unimpeded jets. (604.7.) •Vapour outlets from fuel tanks should be provided with devices tested and type approved to prevent the passage of flame into the tank. (604.8.) •Gas freeing operations should be carried out through outlets at least 3 m above the deck level with a vertical efflux velocity of at least 30 m/s maintained during the gas freeing operation (20 m/s with devices to prevent the passage of flame). (604.10.)
Inert gas availability on board (605)	•Inert gas should be available permanently on board in order to achieve at least one trip from port to port considering maximum consumption of fuel expected and maximum length of trip expected, and to keep tanks inerted during 2 weeks in harbour with minimum port consumption. (605.1.)

	•The production plant, if fitted, should be capable of producing inert gas with oxygen content at no time greater than 5% by volume. (605.4.) •The production plant, if fitted, should be capable of producing inert gas with oxygen content at no time greater than 5% by volume. (605.5.) •Nitrogen pipes should only be led through well ventilated spaces. Nitrogen pipes in enclosed spaces should have only a minimum of flange connections as needed for fitting of valves and be fully welded and be as short as possible. (605.8.)
Pipe design (703)	•All fuel piping and independent fuel tanks should be electrically bonded to the ship's hull. Resistance between piping and the hull should be maximum of 106 Ω. (703.7.) •Filling lines to fuel tanks should be arranged to minimize the possibility for static electricity. (703.9.)
Materials (704)	•Fuel corrosiveness should be considered when selecting materials. (704.1.)
Provisions for bunkering station (803)	•Closed or semi-enclosed bunkering stations should be surrounded by gas and liquid-tight boundaries against enclosed spaces. (803.1.(3)) •Bunkering lines should not be led directly through accommodation, control stations or service spaces. Bunkering lines passing through non-hazardous areas in enclosed spaces should be double walled or located in gastight ducts.. (803.1.(4)) •Arrangements should be made for safe management of fuel spills. Coamings and/or drip trays should be provided below the bunkering connections together with a means of safely collecting and storing spills. (803.1.(5)) •Showers and eye wash stations for emergency usage are to be located in close proximity to areas where the possibility for accidental contact with fuel exists. (803.1.(6)) •Means should be provided for draining any fuel from the bunkering hoses upon completion of operation. (803.2.(2)) •Where fuel hoses are carried on board, arrangements should be made for safe storage of the hoses. Hoses should be stored on the open deck or in a storage room with an independent mechanical extraction ventilation system, providing a minimum of six air changes per hour. (803.2.(3))
General provisions for fuel supply system (903)	•The fuel piping system should be separate from all other piping systems. (903.1.) •The fuel supply system should be arranged such that the consequences of any release of fuel will be minimized, while providing safe access for operation and inspection. The causes and consequences of release of fuel should be subject to special consideration within the risk assessment (903.2.) •The piping system for fuel transfer to the consumers should be designed in a way that a failure of one barrier cannot lead to a leak from the piping system into the surrounding area causing danger to the persons on board, the environment or the ship. (903.3.)

Provisions for fuel distribution (904)	•The outer pipe or duct should be gas and liquid tight. (904.1.) •The annular space between inner and outer pipe should have mechanical ventilation of underpressure type with a capacity of minimum 30 air changes per hour and be ventilated to open air. Appropriate means for detecting leakage into the annular space should be provided. The double wall enclosure should be connected to a suitable draining tank allowing the collection and the detection of any possible leakage. (904.2.)
Redundancy of fuel supply (905)	•Propulsion and power generation arrangements, together with fuel supply systems, should be arranged so that a failure in fuel supply does not lead to an unacceptable loss of power.
Safety functions of the fuel supply system (906)	•All fuel piping should be arranged for gas freeing and inerting. (906.1.) •The main fuel supply line to each consumer or set of consumers should be equipped with an automatically operated master fuel valve. The master fuel valve(s) should be situated in the part of the piping that is outside the machinery space (906.3.) •Means of manual emergency shutdown of fuel supply to the consumers or set of consumers should be provided on the primary and secondary escape routes from the consumer compartment, at a location outside consumer space, outside the fuel preparation space and at the bridge. The activation device should be arranged as a physical button, duly marked and protected against inadvertent operation and operable under emergency lighting. (906.4.) •The fuel supply line to each consumer should be provided with a remotely operated shut-off valve. (906.5.) •Valves should be of the fail-safe type. (906.7.)
Provisions for fuel preparation spaces and pumps (907)	•Any fuel preparation space should not be located within a machinery space of category A, should be gas and liquid tight to surrounding enclosed spaces and vented to open air. (907.1.) •All pumps in the fuel system should be protected against running dry. All pumps which are capable of developing a pressure exceeding the design pressure of the system should be provided with relief valves. Each relief valve should be in closed circuit, i.e. arranged to discharge back to the piping upstream of the suction side of the pump and to effectively limit the pump discharge pressure to the design pressure of the system (907.3.)
Firefighting (1106)	•Where fuel tanks were located on open deck, there should be a fixed fire-fighting system of alcohol-resistant foam type, as set out in chapter 17 of the IBC Code and, where appropriate, chapter 14 of the FSS Code. (1106.1.) •The bunker station should have a fixed fire-extinguishing system of alcohol resistant foam type and a portable dry chemical powder extinguisher or an equivalent extinguisher, located near the entrance of the bunkering station. (1106.3.) •Where fuel tanks are located on open deck, there should be a fixed water spray system

	for diluting eventual spills, cooling and fire prevention. The system should cover exposed parts of the fuel tank (1106.4.) •A fixed fire detection and alarm system complying with FSS Code should be provided for all compartments containing the methyl/ethyl alcohol fuel system (1106.5.) •Suitable detectors should be selected based on the fire characteristics of the fuel. Smoke detectors should be used in combination with detectors which can more effectively detect methyl/ethyl alcohol fires. (1106.6.) •Means to ease detection and recognition of methyl/ethyl alcohol fires in machinery spaces should be provided for fire patrols and for fire-fighting purposes, such as portable heat-detection devices. (1106.7.)
Provisions for control, monitoring, and safety systems (1503)	•Liquid leakage detection should be installed in the protective cofferdams surrounding the fuel tanks, in all ducts around fuel pipes, in fuel preparation spaces, and in other enclosed spaces containing single walled fuel piping or other fuel equipment. (1503.2.) •At least one bilge well with a level indicator should be provided for each enclosed space, where an independent storage tank without a protective cofferdam is located. (1503.4.)
Gas detection (1507)	•Permanently installed gas detectors should be fitted in (1507.1.) (1) all ventilated annular spaces of the double walled fuel pipes; (2) machinery spaces containing fuel equipment or consumers; (3) fuel preparation space; (4) other enclosed spaces containing fuel piping or other fuel equipment without ducting; (5) other enclosed or semi-enclosed spaces where fuel vapours may accumulate; (6) cofferdams and fuel storage hold spaces surrounding fuel tanks; (7) airlocks; (8) ventilation inlets to accommodation and machinery spaces, if required, based on the risk assessment required in 302. •An audible and visible alarm should be activated at a fuel vapour concentration of 20% of the lower explosion limit (LEL). The safety system should be activated at 40% of LEL at two detectors. Special consideration should be given to toxicity in the design process of the detection system.

- Onboard emergency drill and training

The education and training for crews on general merchant ships engaged in international voyages follows the IMO International Convention on Standards of Training, Certification, and Watchkeeping for Seafarers (STCW). Chapter 5-3 of STCW Regulation 5 of the Convention clarifies the crew qualification standards for ships covered by the IGF Code as follows.

[Table 5-5] Crew qualification standards for ships covered by the IGF Code under STCW regulation

8. Every candidate for a certificate in advanced training for service on ships subject to the IGF Code shall, while holding the Certificate of Proficiency described in paragraph 4, have: 1. completed approved advanced training for service on ships subject to the IGF Code and meet the standard of competence as specified in section A-V/3, paragraph 2 of the STCW Code; and 2. completed at least one month of approved seagoing service that includes a minimum of three bunkering operations on board ships subject to the IGF Code. Two of the three bunkering operations may be replaced by approved simulator training on bunkering operations as part of the training in paragraph 8.1 above. 9. 1. Masters, engineer officers and any person with immediate responsibility for the care and use of fuels on ships subject to the IGF Code who have been qualified and certified according to the standards of competence specified in section A-V/1-2, paragraph 2 for service on liquefied gas tankers are to be considered as having met the requirements specified in section A-V/3, paragraph 2 for advanced training for ships subject to the IGF Code, provided they have also: 1. met the requirements of paragraph 6; and 2. met the bunkering requirements of paragraph 8.2 or have participated in conducting three cargo operations on board the liquefied gas tanker; and 3. have completed sea going service of three months in the previous five years on board: 1. ships subject to the IGF Code 2. tankers carrying as cargo, fuels covered by the IGF Code;or 3. ships using gases or low flashpoint fuel as fuel.

Chapter 8 of the IGF Code (IMO Resolution MSC.285(86)) describes the basic requirements for operations and training, but as it is a recommendation rather than a mandate, the state party should take responsibility for the education and training of the crew of ships using low-flashpoint fuels.

The requirements for onboard emergency drills stipulated by IMO's Interim Guidelines for the Safety of Ships Using Methyl/Ethyl Alcohol as Fuel (MSC.1/Circ.1621) and Appendix 5: Requirement for Ships Using Methyl/Ethyl Alcohol As Fuel" in the KR Rules for Ships Using Low-flashpoint Fuels can be found in the following Table 5-6.

[Table 5-6] Requirements for onboard emergency drill regarding the low-flashpoint fuel ships rules

16 in Appendix 5 in KR Rules for Ships Using Low-flashpoint Fuels 1601. Training, drills and emergency exercises The goal of this section is to ensure that seafarers on board ships to which these Interim Guidelines apply are adequately qualified, trained and experienced 1. fuel-related drills and exercises should be incorporated into the schedule for periodical drills 2. review of fuelling procedures based on the fuel handling manual required by Chapter 17, 101.2 3. The response and safety system for hazards and accident control should be reviewed and tested 4. The company should ensure that seafarers on board ships using methyl/ethyl alcohol fuels should have completed training to attain the abilities that are appropriate to the capacity to be filled, and duties and responsibilities to be taken up. 5. The master, officers, ratings and other personnel on ships using methyl/ethyl alcohol fuels should be trained and qualified in accordance with regulation V/3 of the STCW Convention and section A-V/3 of the STCW Code, taking into account the specific hazards of the methyl/ethyl alcohol used as fuel
17 in KR Rules for Ships Using Low-flashpoint Fuels 101. General details 2. Drills and exercises should be incorporated into the schedule for periodical drills, including the followings but not limited to. (1) tabletop exercise; (2) review of fuelling procedures based on the fuel handling manual required by Chapter 18, 201.3; (3) responses to potential contingencies; (4) tests of equipment intended for contingency response; (5) reviews that assigned seafarers are trained to perform assigned duties during fuelling, operation and contingency response

As methanol is a dangerous substance that causes numerous safety accidents (e.g., poisoning and blindness), a safety training on methanol handling is required in addition to general fuel-related training, but there is still not enough training on methanol handling and methanol engines for crews. Therefore, it is necessary to provide more training programs. On land, for example, the Korea Occupational Safety and Health Agency provides safety training for workplaces involving the usage of methyl alcohol, and the ten rules of chemical safety and health management are as follows.

(1) Before handling methanol, the employer must obtain the material safety data sheet (MSDS) and be aware of the hazards and risks. (see Table 5-1 for the hazards/risks of methanol).

(2) Post the MSDS in a place where it is easily visible to workers and ensure that warning signs are affixed to containers, etc.

(3) Provide training to workers on the effects of methanol on the human body and precautions during handling. (see Table 5-1)

(4) Ensure that sources of methanol emissions are sealed or ventilated to prevent exposure during

work.

(5) Ensure that workers are provided with and wear appropriate personal protective equipment (e.g., respirators for protection, protective clothing, etc.) when handling methanol in person.

(6) Regularly measure and evaluate the working environment and improve the environment.

(7) Conduct special medical examinations regularly to manage the health of workers.

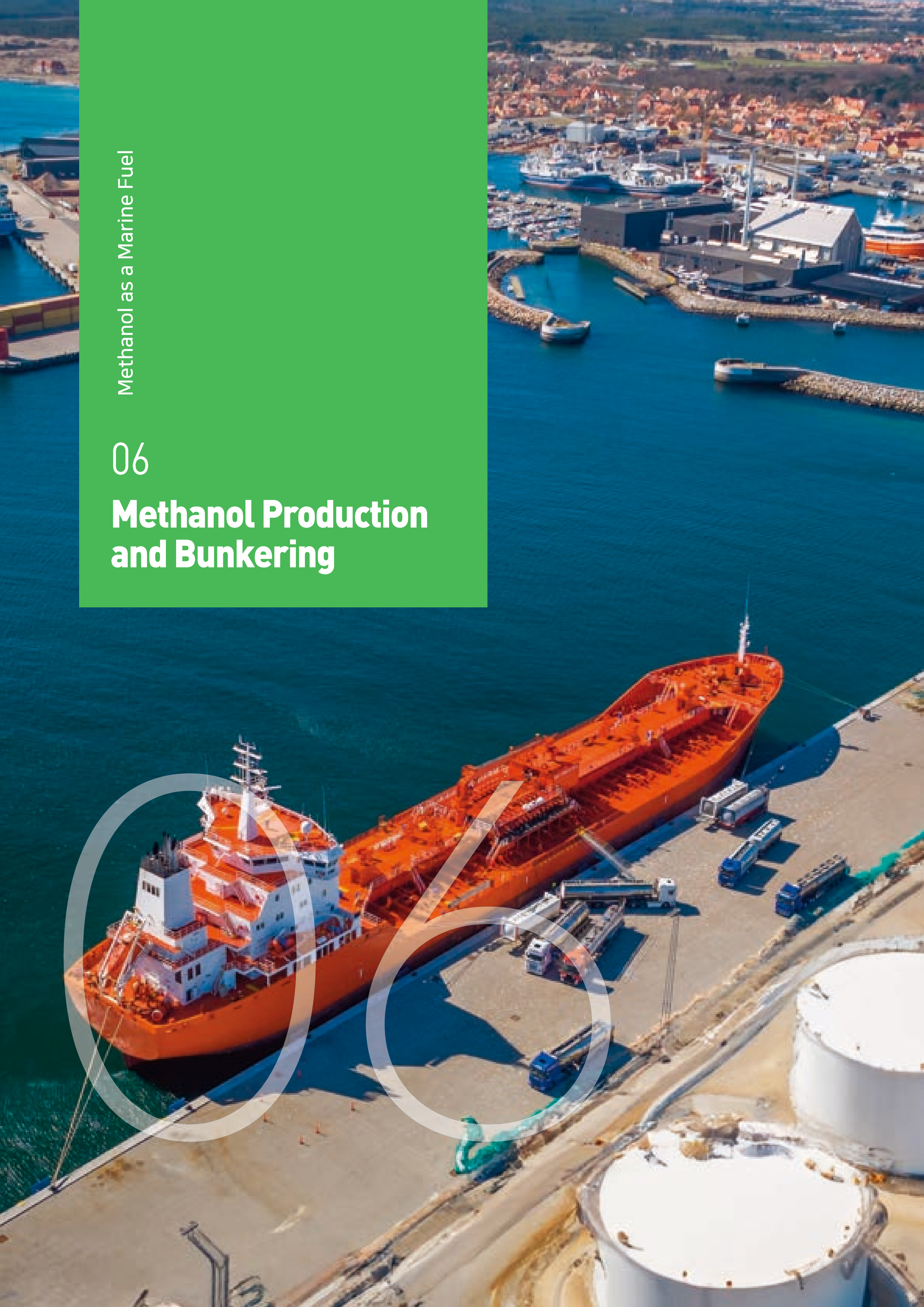
(8) Install cleaning facilities and wash work clothes and exposed body parts after work.

(9) Prohibit smoking and eating in indoor workplaces where methanol is handled in person.

(10) Report any physical abnormalities, such as vomiting, difficulty breathing, or rashes, caused by handling methanol and seek appropriate medical attention.

06

Methanol Production and Bunkering



6.1. International Production Status and Outlook for Eco-friendly Methanol

As mentioned in Chapter 2, eco-friendly can be divided into blue methanol and green methanol, based on the source of input material and the production pathway. The green methanol can be further divided into bio-methanol and e-methanol. Bio-methanol is synthesized from biogas, which is obtained from Municipal Solid Waste (MSW) or through gasification of biomass E-methanol refers to methanol obtained by reacting green hydrogen obtained through water electrolysis using renewable energy with carbon dioxide.

- Bio-methanol

As of 2022, less than 200,000 tons of eco-friendly methanol is produced the majority of which is bio-methanol. The most commonly used method is gasification of various biomass to produce synthetic gas, from which methanol is synthesized. Various companies are test-operating gasification processes for biomass/municipal waste through large-scale pilot plants. Representative gasification projects can be found in Table 6-2. As of 2021, test-operations of gasification projects to obtain long-operation data have reached a capacity of 1.7Mt/y, preparing for full-scale process design and commercialization. These demonstration projects correspond to a level higher than the Technology Readiness Level (TRL) of 8 or 9.

[Table 6-1] Gasification technology-related abbreviations [29].

Abbreviation	Meaning	Note
DO_2	Directly (D) heated via partial combustion with O_2	Heating principle
IH	Indirectly heated	Heating principle
BB	Bubbling bed principle	Gasifier type
UO_2	Updraft, O_2 injected together with steam	Gasifier type
EF	Entrained flow (fuel and O_2 injected together in a burner device)	Gasifier type
U-IH	Updraft, indirectly heated	Gasifier type

[Table 6-2] Gasification technology-related abbreviation [29].

Company	Heat Source	Type	Raw Materials	Project Name	Stage	Product	Capacity
SES Gasification Technology (U-Gas)	DO_2	BB	Biomass /MSW	Trans World Energy, Florida (US)	FEED completed, Start-up in Q2 2023	Methanol	875kt/y
NextChem Technology	DO_2	UO_2	MSW	ENI Refinery, Livorno, Italian (IT)	Basic engineering ready (Q3 2020)	Methanol	115kt/y
			MSW/ waste food	LowLand Methanol (NL)	Planned start-up in 2023	Methanol	120kt/y
PDQ/Thys-senkrupp	DO_2	EF	Biomass (torrefied)	BioTfuel, Demo Project (FR)	In operation	FT-Fuel	15MWt biomass
HTW/Thys-senkrupp	DO_2	BB	Biomass	Värmlands-metanol (SE)	In plan	Methanol	100kt/y
TRI	IH	BB	MSW	Fulcrum (US)	2020 Q4 start-up	FT-Fuel	40,000m^3/y
Bioliq/KIT	DO_2	EF	Pyrolysis oil from straw	Bioliq Demo project (DE)	In operation	DME	5MWt biomass
Chemrec	DO_2	EF	Black liquor	BioDME demo plant (SE)	In delay	DME	4t/d
Enerkem	DO_2	BB	MSW	Edmonton (CA)	In operation	Ethanol	30kt/y
	DO_2	BB	MSW	Quebec (CA)	Construction confirmed	Ethanol	35kt/y
	DO_2	BB	MSW	Rotterdam (NL)	Engineering	Methanol	215kt/y
	DO_2	BB	MSW	Saragossa (SP)	Engineering	Methanol	215kt/y
Sungas and GTI	DO_2	BB	Biomass	GTI demo, Chicago (US)	In operation	Synthetic gas	5MWt biomass
TCG Global	IH	U-IH	Biomass	Red Rock Biofuels	Start-up in 2021	FT-Fuel	58,000m^3/y

Some of the representative MSW gasification projects are the projects operating in Canada by Enerkem. Enerkem has operated MSW gasification-based methanol production plants for approximately 10,000 hours from 2015 to 2019, and produced 4 million liters of methanol in 2019 through gasification of 60 kt of MSW. In 2018, a process for converting methanol to ethanol was added in parallel for simultaneous production. Most projects in Table 6-2 use water gas shift (WGS) reactors to match the ratio of hydrogen to carbon monoxide, but Enerkem's Quebec, Rotterdam, and Saragossa projects and LowLands Methanol's project employ externally supplied green hydrogen to make-up for the insufficient hydrogen, combining bio- and e-methanol pathways to produce methanol. As for Enerkem's Quebec project, the installation of an 87 MW water electrolysis device dedicated to the supply of green hydrogen is expected to increase annual bio-methanol production to 100 kt/y.

The method of producing bio-methanol from biomethane that is separated from naturally generating biogas in waste treatment processes, is also receiving a lot of attention. Biogas is formed from the microbial decomposition of organic matter in landfills and sewage treatment, and is widely utilized in Europe, but is mostly mixed with natural gas to be utilized for local power generation and district heating. In some projects, biogas is being mixed with natural gas and utilized in commercial methanol production processes. BASF has been producing methanol by utilizing a mixture of natural gas and biogas in the methanol production process in Ludwigshafen since 2018. The utilization of a mixture of natural gas and biogas has led to reduced greenhouse gas (GHG) emissions by approximately 50% compared to conventional methanol production processes, and has been certified by the Renewable Energy Directive (RED). OCI/BioMCN has taken a similar approach to BASF's method, and has produced bio-methanol since 2009. BioMCN's bio-methanol production capacity reaches 60,000 t/y, and the company has plans to expand the production capacity after receiving an International Sustainability Carbon Certificate from DEKRA. It is also conducting research on producing high-quality methanol by refining low-quality methanol produced as a byproduct from pulp production processes. When wood pulp is reacted with sodium hydroxide and sodium sulfate in the pulp production process, methanol is produced as a by-product, which is generally low in purity and consequently has previously been recycled as an energy source in the process. With additional refining processes it is possible to produce high-quality methanol, and companies such as Sodra in Sweden and Alberta Pacific in Canada are conducting projects to develop such processes. Sodra has begun the development of a process capable of producing AA-grade methanol from a sawmill at a scale of 5250 t/y from 2020, expecting to achieve a 98% GHG emission reduction compared to conventional methanol production processes. Alberta Pacific has been refining methanol at its Boyle Mill in Alberta for in-process use since 2012, and has recently begun process development in collaboration with Oberon Fuels to produce 17,000 L/d of dimethyl ether (DME) from its pulp process.

- E-methanol

The biggest obstacle to the large-scale production of e-methanol is the absence of large-scale water electrolyzers. Catalysts for the reaction of carbon dioxide and hydrogen to produce methanol have already been developed and have been/are being commercialized by companies such as Halder Topsoe, Johnson Matthey and Clariant. However, the synthesis of e-methanol requires three molecules of green hydrogen for every one molecule of carbon dioxide, which amounts to 10-11 MWh of electricity to produce one ton of methanol. The operation of a medium-sized methanol plant, for example a 1000 t/d process, requires a water electrolysis device with a 420 MW capacity; the replacement of the current commercially available large-scale methanol plants requires 2500 t/d methanol production, which requires a GW-scale water electrolyzer. Although water electrolyzers in the scale of 100MW are currently in operation, more research and development are required to develop water electrolyzers with an even larger scale.

Carbon Recycling International (CRI) built the first commercial plant in Iceland in 2011 producing e-methanol through the hydrogenation of carbon dioxide. The annual methanol production capacity is 4,000 tons, and energy cost saving has been made available through integration with geothermal power. In China, the Dalian Institute of Chemical Physics commenced development of a demonstration project to produce 1000 tons of methanol per year. Green hydrogen is supplied by an alkaline water electrolyzer with a capacity of 1000Nm^3/h, while enabling hydrogen production through renewable energy by connecting to solar panels with a 10MW capacity. Around the world, additional demonstration plants are scheduled for development, adding up to a scale of 8,000-18,000 tons of methanol per year. If all the planned plants can be commercialized, it is estimated that 700,000 tons of e-methanol could be produced annually in the future. Table 6-3 shows the major e-methanol projects around the world.

Country	Company	Start-up year	Capacity (t/y)	Raw material
Iceland	CRI	2011	4000	CO_2 from geothermal power, H_2 from water electrolysis
China	Dalian Institute of Chemi-cal Physics	2020	1000	CO_2, H_2 from PV water electrolysis
Sweden	Liquid Wind	2023	45000	Upcycled industrial CO_2, H_2 from water electrolysis
Australia	ABEL	2023	60000	Biogenic CO_2, H_2 from water electrolysis
China	Henan Shuncheng Group/CRI	2022	110000	CO_2 from limekiln, coke oven gas H_2
Norway	Swiss Liquid Future/ Thysenkrupp	n/k	80000	CO_2 from ferrosilicon plant, H2 from hydroelectric water electrolysis
Norway	Consortium of companies/CRI	2024	100000	CO_2, H_2 from water electrolysis
Canada	Renewable Hydrogen Canada (RH_2C)	n/k	120000	CO_2, H_2 from hydroelectric water electrolysis
Belgium	Consortium at the port of Antwerp	n/k	8000	CO_2, H_2 from water electrolysis
Belgium	Consortium at the port of Ghent	n/k	46000-180000	CO_2 from Industries, H_2 from water electrolysis
Netherlands	Consortium of Nouryon/Gasunie/BioMCN and 3 others	n/k	15000	CO_2, H_2 from water electrolysis
Germany	Dow	n/k	-200000	CO_2, H_2 from water electrolysis
Denmark	Consortium of companies	2023-2030	n/k	CO_2 from MSW/biomass, H_2 from wind water electrolysis
Germany	Consortium	n/k	n/k	CO_2 from cement plant, H_2 from water electrolysis

[Table 6-3] E-methanol projects in operation or planned globally [29].

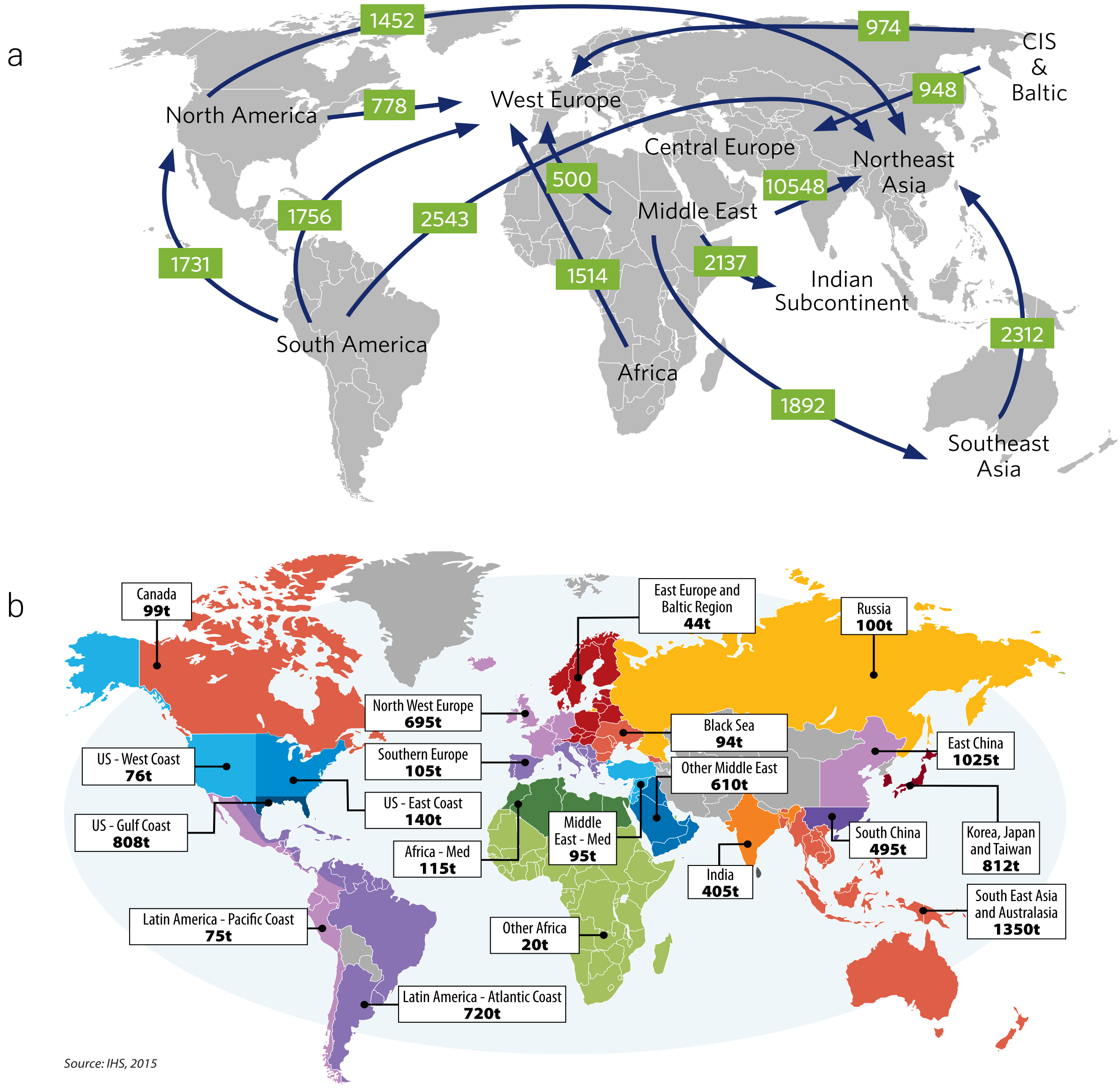
6.2. Methanol Market and Outlook

- Methanol market size and future outlook

120 million tons of methanol is annually produced in about 90 production sites globally, and 33% of the produced methanol is exported overseas through approximately 120 ports (Figure 6-1). This has the second-largest production volume after ammonia, and is the second-most shipped chemical in the world after palm oil [28]. These features also favor the supply of methanol as a fuel.

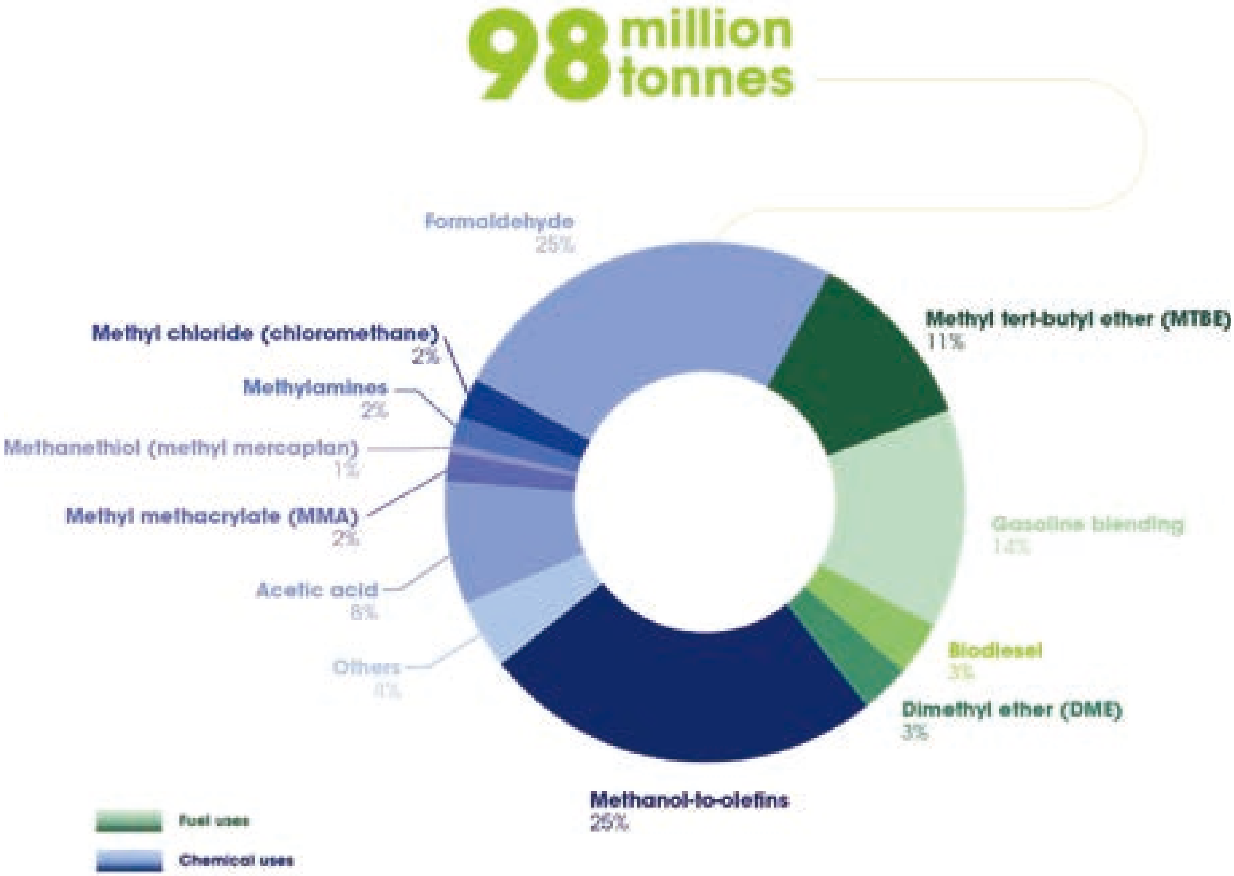
As shown in Figure 6-2, more than 60% of the produced methanol is used as an input material for other chemicals, examples of which include formaldehyde production (25%), olefin production through the methanol-to-olefin (MTO) process (25%), acetic acid production (8%), and MMA (2%). These chemicals are processed and applied in everyday products such as paints, plastics, and building materials. Formaldehyde accounts for the largest share of methanol conversion products and is used to produce phenol formaldehyde, urea formaldehyde, melamine formaldehyde, polyacetal resins, and MDI (methylenebis(4-phenyl isocyanante)). MDI is widely utilized as insulators in refrigerators and automobiles, and formaldehyde resins are used as adhesives in the wood industry. The MTO process has seen a dramatic increase in demand since the 2010s, especially in China, and has accounted for a large share in producing plastics such as polyethylene and polypropylene [88]. When methanol is used directly, it is utilized as a solvent, antifreeze, and screen cleaner [89].

Demand for methanol as a fuel has also steadily increased since the mid-2000s, with approximately 31% of total methanol demand being currently used as a direct fuel or converted into other fuels such as biodiesel, methyl tert-butyl ether (MTBE), and dimethyl ether (DME) [29]. In the case of directly utilizing methanol, it is mainly utilized in gasoline internal combustion engines, but can also be applied to modified diesel engines or fuel cell vehicles. When mixed with gasoline, it is mainly utilized as a vehicle fuel, such as in M85 vehicles (85% methanol, and 15% gasoline), or GEM (Gasoline, Ethanol, Methanol) vehicles, which can utilize various ratios [90]. As for MTBE, it is widely used as an additive to prevent knocking in gasoline engines and while its utilization is banned in some regions due to concerns over groundwater contamination, use is increasing, especially in Asia and Mexico. As for DME, it can be produced by the dehydration reaction of two molecules of methanol, and it exists as a gas at normal pressure, but it is liquefied through pressurization and used as a substitute for propane in LPG.



|Figure 6-1| Interregional methanol import/export routes and flow rates (Unit: 1000t/y)

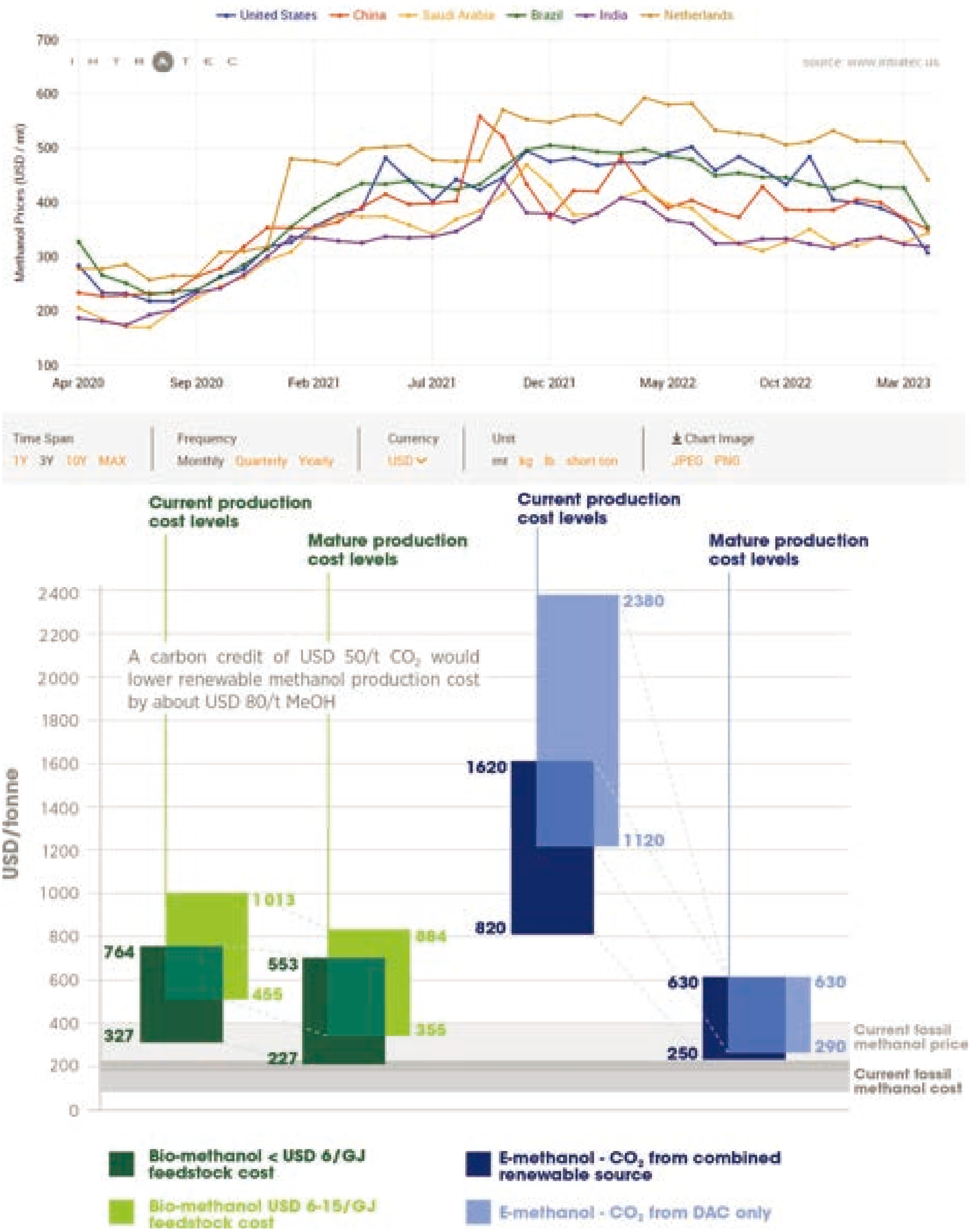
The methanol market size expected to increase in the future. Based on current increase rates, methanol production could increase to 120 million tons by 2025 and 500 million tons by 2050. As demand for the MTO process is growing, especially in China, the increase in methanol produced for purposes such as formaldehyde and fuel production is expected to be relatively small, and the increase in production for MTO is expected to be large. Additionally, the demand for e-methanol and bio-methanol as alternative fuels is expected to significantly increase due to the transition towards a decarbonized society. In Europe, Vulcanol produced by CRI and bio-methanol produced by BioMCN in the Netherlands are currently utilized adding it to conventional fuel; in the UK, 57 million liters of bio-methanol were utilized by blending it with gasoline in 2018 [91]. Assuming that the M3 standard (the regulation on the use of 3 vol% methanol blended with gasoline, EN 228), which is a regulation on the utilization of eco-friendly methanol, is applied and methanol-blended gasoline is used throughout Europe, it is estimated that approximately 2.5 million tons of eco-friendly methanol production will be required. Considering that there are more regulations to come in recent years for the use of alternative fuels not only in vehicles, but also in ships and airplanes, the global market for methanol as a fuel is expected to reach 2 billion tons [29].



|Figure 6-2| Annual methanol production and use in 2019 [29].

- Methanol prices and future outlook

Current expectations for green methanol are high, but there are still limitations in economic feasibility and production capacity that need to be overcome. As shown in Figure 6-3, brown/gray methanol is priced at approximately $300-500/t in the market. On the other hand, as indicated in Figure 6-4, bio-methanol shows a high production cost of approximately $300-1000/t, and e-methanol has a much higher production cost of $800-2300/t.



|Figure 6-4| Current bio-methanol, e-methanol production unit price and future outlook [29].

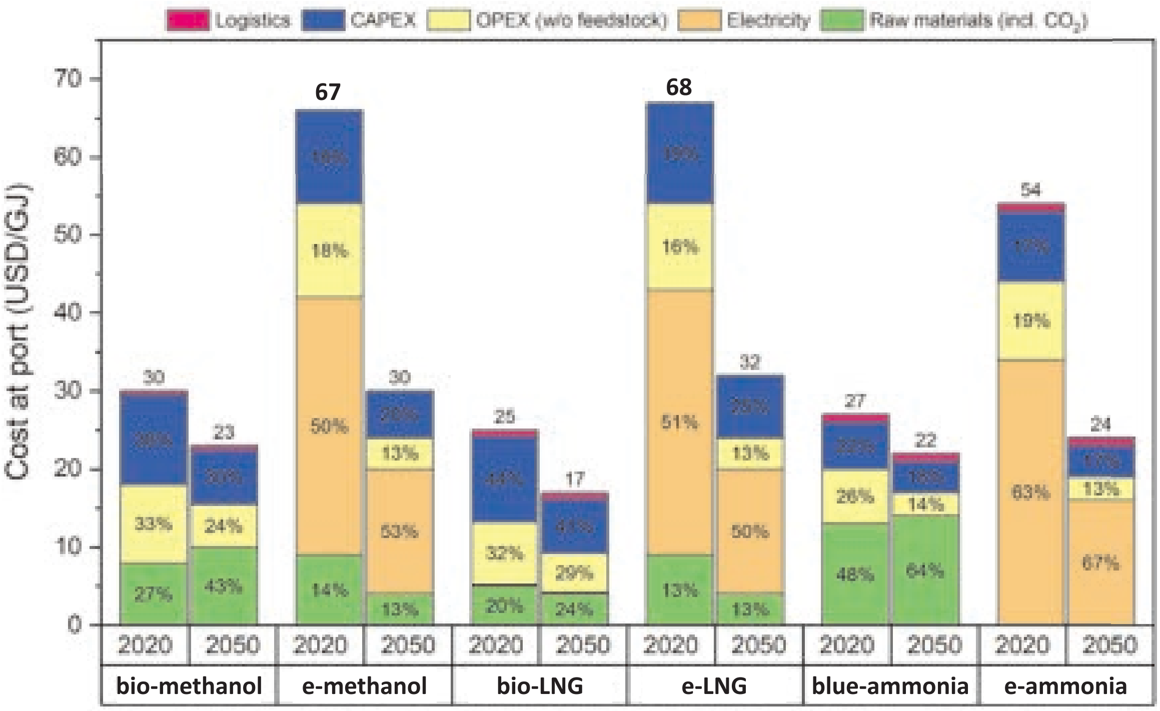
In terms of bio-methanol, factors such as securing arable land for biomass production and changes in biomass production capacity depending on the season must be addressed to mitigate large price fluctuations. Especially, the unit cost of raw materials has a significant impact on the production cost. Considering that the upper limit price of biomass and MSW that are commercially distributed in Europe and the United States, is \$6/GJ, bio-methanol is estimated to be priced at approximately \$327-764/t; but if the unit price of raw materials reaches \$6-15/GJ, the unit cost of production will increase to approximately 1000\$/t. If the process is optimized and empirical improvements are made, it is expected that bio-methanol will be able to be produced at a price of 227-884\$/t in future.

As for e-methanol, the biggest obstacle large-scale production is how to secure green hydrogen and renewable carbon dioxide, and their unit prices. Since the production process of methanol by reacting CO_2 and H_2 has a high technology readiness level of higher than TRL 9 and scale-up is readily available, it seems possible to totally replace the conventional methanol production process currently in operation. However, the production of 1 ton of green hydrogen requires 50MWh of renewable energy-based power, and there is still not enough renewable energy-based power generation to meet the demand for green hydrogen. The production cost of e-methanol is currently estimated at \$820-2,380/t, which is higher than the production cost of bio-methanol. This is because of the high cost of electricity for water electrolysis stage to produce green hydrogen.

In addition, the source of CO_2 should be stably secured. In the short-term, CO_2 captured from point sources such as coal-fired power plants can be used, but this is non-renewable CO_2 that cannot reduce WtW GHG emissions. To satisfy the long-term target of CO_2 reduction, bio-based CO_2 or CO_2 obtained from Direct Air Capture (DAC) should be available. Since the current cost of CO_2 obtained via DAC is highly costly, e-methanol produced using CO_2 through DAC has a very high unit cost of production of \$1100-2300/t. Since the cost competitiveness of e-methanol is significantly influenced by the unit price of electricity and the prices of CO_2 and H_2, factors such as cost reduction of renewable energy, high technology readiness of water electrolyzers, and cost reduction of CO_2 capture process should be additionally satisfied to reach the unit cost of production of 250-630\$/t in future.

Figure 6-5 shows the cost per unit of energy and its cost breakdown for the production processes of methanol, LNG, and ammonia. The overall production cost of e-fuel is currently higher than that of biofuel; as for the cost breakdown, the electricity cost required for producing e-fuel accounts for a very high proportion of more than 50% in all cases, leading to high production costs. For bio-methanol, the cost of raw materials is expected to increase over time due to a higher demand for biomass. On the other hand, the cost of biomethane raw material is expected to remain at a similar level, because inexpensive bio-raw materials such as MSW, sludge, and agricultural waste can be used for biomethane. As for bio-based processes, the price and the demand and supply of bio-raw materials, and in the case of electricity-based processes, the cost of electricity is expected to be a major factor for determining the future cost competitiveness.

In short, the current unit cost of production for both bio-methanol and e-methanol is higher than that of conventional methanol production methods, and in order to be competitive, process maturity and cost reduction of renewable energy should be achieved. In addition, if cost subsidies for green methanol via policies can be provided through carbon credits, the commercialization of green methanol could be accelerated.



|Figure 6-5| Expected cost structure and future cost changes for green methanol, LNG, and ammonia [93-95].

6.3. Status of methanol bunkering infrastructure

Since methanol exists in a liquid state at atmospheric temperature and pressure, the methanol bunkering system has a similar configuration with the conventionally used bunkering system of MGO and HFO. As existing bunkering facilities can be converted to facilities for methanol through some device modifications, the number of methanol ports are increasing in line with the recent trend of increased operations of methanol-fueled ships. Different types of methanol bunkering include the use of trucks, barges, and terminals.

Methanol bunkering via trucks has been in use since 2015. As for Stena Germanica, the world's first commercial ferry operated by Stena Line, methanol bunkering via truck has been carried out since 2015. In addition, as commercial ferries such as MV Undine, Stena Scanrail, and Viking Mariella have also utilized trucks for methanol bunkering and they have abundant experience in loading, transporting, and unloading during methanol bunkering [39].

Bunkering using barges is a form of delivering methanol to ships anchored in ports or offshore. Barge-based bunkering was first demonstrated in the Port of Rotterdam in 2021. Methanol bunkering was carried out from MTS Evidence's barge on Takaroa Sun, Waterfront Shipping's 49,800 DWT methanol dual-engine vessel; through this process, it was confirmed that a stable methanol bunkering is possible to be carried out via safety equipment and procedures similar to that of MGO or HFO bunkering [39]. After this demonstration, additional construction orders for methanol bunkering vessels were placed in ports of Rotterdam in the Netherlands, Norway, and Singapore. At the port of Antwerp in Belgium, 475 tons of methanol bunkering was carried out in June 2023. Bunkering was progressed from the barge Tamariva to Proman Stena Marine; the Port of Antwerp plans to become a port that can handle a variety of low-carbon fuels by 2025. The cost of installing a new unit for methanol bunkering is estimated to be approximately €400,000, and the cost of converting an existing barge for the purpose of methanol bunkering, is estimated to be approximately €1.5 million [66].

|Figure 6-6| Methanol bunkering using tank vehicles of the Stena Germanica vessel [66].

As for large-capacity vessels that operate regularly, bunkering using terminals is an efficient option. Various projects for bunkering at terminals are currently in progress: for example, in 2022, China Shipbuilding Hengyu Energy, a subsidiary of CSSC, bunkered 240 tons of methanol on three 49,000-ton ships [39]. There are recent efforts to designate routes between major ports as "Green Corridors" and to promote the development of technological and economic cooperation between the government and the private sector to achieve zero-emission shipping/marine transport; it is expected that methanol terminal bunkering ports will further increase around such routes [21].

Standard documents are also being created to expand methanol bunkering facilities. In 2020, Lloyd's Register produced a technical reference document for methanol bunkering [96]. Since the document includes a checklist highlighting methanol bunkering, it provides a standard ensuring that safe bunkering can be achieved based on a common technical document for all stakeholders. In addition, the International Association of Ports and Harbors (IAPH) is producing a checklist for methanol bunkers, and the Ports of Rotterdam and Singapore are also preparing guidelines for methanol bunkering. The current status of the methanol bunkering projects can be found in Table 6-4.

[Table 6-4] Status of methanol bunkering.

Bunkering equipment	Ship	Port	Year
Truck	Stena Germanica	-	2015-
Truck	MV Undine	-	2010
Truck	Stena Scanrail	-	2013-2014
Truck	Viking Mariella	-	2018
Barge	MTS Evidence→Takaroa Sun	Rotterdam	2021
Barge	Tamariva→Stena Pro Marine	Antwerp - Brugge	2023
Barge	Stena Pro Marine Stena Prosperous	Houston	2023
Barge	Stena Germanica	Gothenburg	2023
Barge	Stena Pro Marine Stena Pro Patria	Ulsan	2022
Terminal	CSSC Hengyu Energy	-	2022
Pipe	A.P. Moller-Maersk	Ulsan	2023

07

Prospects of Methanol as a Marine Fuel

7.1. Comparison with LNG

- GHG emissions reduction

In terms of WtW GHG emissions intensity, gray methanol has the intensity of 100.4 g_{CO2eq}/MJ, which has no advantage compared to conventional fossil fuels (90-94 g_{CO2eq}/MJ) or LNG (76.1-89.2 g_{CO2eq}/MJ). (Table 7-1). However, bio-methanol or e-methanol may have relative advantages compared to bio-methane and e-LNG. Bio-methanol is evaluated to have relatively low WtW emissions intensity of 10.4-16.2 g_{CO2eq}/MJ. Bio-methane can have a wide range of intensity from the lowest of -98.5 g_{CO2eq}/MJ to the highest of 87.4 g_{CO2eq}/MJ depending on the types of raw materials and processes used which makes it difficult to compare it with other fuels. However, considering that additional energy is required for liquefaction and transportation to produce LNG, bio-methanol may have some advantages in the transportation stage. Based on the same logic, as for e-methanol and e-LNG, e-methanol is assumed to have advantages to some extent in terms of transportation.

- Ecological impact and risk

Based on PM10 (Particular Matter 10, fine dust with a diameter of 10μm or less), which is one of the indicators for determining air pollution, methanol is known to rarely generate PM10, and LNG also emits very low fine dust of approximately 0.01 g/MJ. As for an acceptable toxic leakage level in case of spilling into the ocean, methanol has a very low toxicity in water of 15,400 mg/L, compared to LNG (50 mg/L) (Table 7-1). The flash points of methanol and LNG are 11℃ and -161.5℃, respectively; as both of them are lower than atmospheric temperature, there is a possibility of explosion in the presence of an ignition source. The kinematic coefficient of viscosity of LNG in the liquid phase is 17.2 cSt, which is lower than that of methanol (0.7 cSt), but in case of leakage, greater damage is expected in case of diffusion and leakage because it quickly vaporizes due to a large temperature difference, and is explosive.

- Availability and technical status

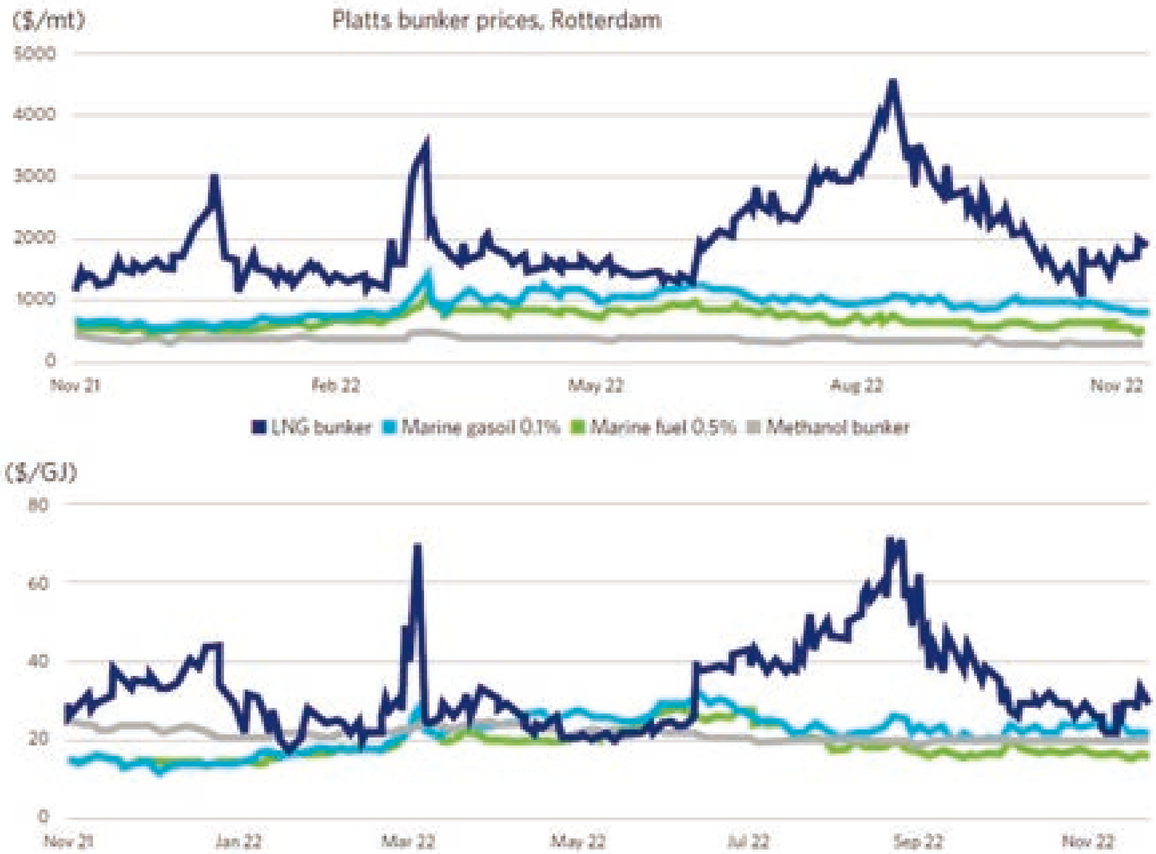
In terms of LNG, bunkering infrastructure is currently established in approximately 80 places around the world, mainly in large ports, while there are only approximately 10 bunkering cases for methanol ships. However, as previously mentioned in Section 6.2, there are approximately 120 ports around the world that can procure methanol, and if demand for methanol vessels increases in the future, bunkering infrastructure can also be expected to be expanded.

Methanol has approximately 36% of the heating value (MJ/kg) and 60% of the energy density (MJ/L) compared to LNG. Therefore, the fuel storage space can be larger for methanol, but when considering cryogenic insulation and cargo handling systems, the relative size of the entire cargo handling system is estimated to have no significant difference, at approximately 2.3 times that of the HFO (Table 7-2). This is because, unlike LNG, which must be maintained at a cryogenic storage temperature of around -162°C, methanol can be stored at atmospheric temperature and pressure, so there is no need for additional insulation or large boil-off gas treatment systems.

The engine technology of both fuels has high technology readiness of TRL 9, combustion conditions are similar, and dual fuel engine technology that can be used in combination with existing fuels has been commercialized. Consequently, it is expected that economic feasibility can be maximized by adjusting the use ratio of both methanol and LNG to existing fuels while satisfying IMO regulations.

- Economic feasibility

Fuel prices show high fluctuations depending on the period, production methods and regions, making it difficult for comparisons. As of 2021, gray methanol was approximately $20/GJ, and that of gray LNG was at an average of $17.6/GJ, indicating that methanol had a slightly higher price range than LNG (Table 7-2). However, since the LNG price volatility has been very large in recent years, and some regions face a price range of more than twice that of methanol, a simple comparison is difficult to make (Figure 7-1). As for green methanol, the prices of bio-methanol and e-methanol are expected to be $30.0/GJ and $66.0/GJ, respectively, which is assumed to be approximately 1.5 - 3 times higher than gray methanol. As mentioned earlier in Section 6.2, the potential exists to produce green methanol at the level of $23-30/GJ in the future, by stabilizing biomass raw material prices, optimizing processes, stabilizing CO_2 capture process price, achieving high technology readiness of water electrolysis device, and reducing renewable energy costs in the future, which is assumed to be possible to compete with existing LNG to some extent (Figure 7-3). Bio-LNG is evaluated to have a unit production cost that is more than twice that of gray LNG, but it is also estimated that it can be produced at a lower cost than bio-methanol and e-methanol; considering that, it is assumed to be in demand for a considerable period of time. In the case of e-LNG, it is deemed to have a cost range higher than that of e-methanol, which may be relatively disadvantageous in consideration of the process of storing and transporting low-temperature fluids.



|Figure 7-1| (Top) Change in bunkering price of HFO, MGO, LNG, and methanol ($/ton) and (Bottom) Change in price per energy by fuel ($/GJ) [26].

[Table 7-1] Comparison summary of GHG emissions per main fuel for vessels, ecological impact, and risk [84, 97-105].

			WtT						TtW						WtW	Ecological impact and risk			
			CO_2	CH_4	N_2O	NO_x	SO_x	GHG intensity	CO_2	CH_4	N_2O	NO_x	SO_x	GHG intensity	GHG intensity	PM10	Toxicity (LC50)	Flash point	Kinematic viscosity
Unit			g/MJ	mg/MJ				gCO2e/MJ	g/MJ	mg/MJ				gCO2e/MJ	gCO2e/MJ	g/MJ	mg/L	℃	cSt
Conventional	HFO		11	99	0.25	22	2.5	13.5	77	1.5	4.2	2100	560	78.2	91.7	0.20	79	60	377.5
	MGO		13	108	0.23	22	3	14.4	75	1.4	4.1	700	101	76.4		0.04	8	52	3700
Alternative fuels	LNG		27	33	0.16	50	12	18.5	56	356	1.6	700	2	57.6~70.7	76.1~89.2	0.01	50	-175	17.2
	Methanol	Gray	29	11	0.29	46	2.1	31.3	60	0	0	340	2	69.1	100.4	0	15400	12	0.7
		Green	3	42	0.22	56	48	-56.4~-40.8	0	8	2.3	340	N/A	69.0	10.4~28.2				
	Hydrogen	Gray	81	320	1.38	66	54	132.0	0	0	0	0	0	0.0	132.0	0	-	Flammable gas	-
		Green	9	2.8	0.41	35	58	Below 28.2	0	0	0	0	0	0.0	Below 28.2				
	Ammonia	Gray	75	5.3	0.45	44	0.44	121.0	0	0	17.8	N/A	N/A	0.0	121.0	0	0.07	132	0.2
		Green	24	N/A	0.45	44	N/A	Below 28.2	0	0	17.8	N/A	N/A	0.0	Below 28.2				
	Bio-diesel		57	25	44	105	35	-65.7~-0.9	1	10	3.0	935	500	64.4~76.6	14.9~75.7	0.05	57	150	3.0

* The GHG emissions intensity in this table are based on FuelEU Maritime/ REDII (Table 2-8), and it may be diferenent by literature.
* TtW GHG emissions intensity of ammonia are set at 0, but this value does not yet reflect the influence of N_2O.
* GHG intensity of e-fuel is based on a reduction of more than 70% compared to the IMO fossil fuel standard (94 g_{CO2eq}/MJ).

[Table 7-2] Comparison summary of energy characteristics, operating conditions, economic feasibility, and output per main raw material of vessel [64, 93-95, 100, 106-115].

			Energy		Storage		Engine				Economic feasibility				Capacity
			LHV	Energy density	Relative space	Temp. (@1bar)	TRL	Minimum ignition energy	Auto-ignition Temp.	Maximum flame velocity	Engine	Engine modification	Cost (2021)		Annual
Units			MJ/kg	MJ/L		℃	-	mJ	℃	m/s			$/kg	$/GJ	10^6 tonne/yr
Conventional	HFO		40.5	37.6	1	25	9	-	300	-	low	-	0.40	9.9	250
	MGO		42.7	36.6	1	25	9	-	375	-	low	-	0.50	11.7	10
Alternative fuels	LNG		49.1	25.0	2.3	-162	9	0.3	540	0.34	medium	medium	0.86	17.6	400
	Methanol	Gray	19.9	15.8	2.3	25	9	0.14	464	0.43	low	low	0.40	20.1	120
		Green(bio-)											0.60	30.0	-
		Green(e-)											1.31	66.0	-
	Ammonia	Gray	18.6	12.7	4.1	-34	6	8	651	0.015	medium	-	0.25	13.4	180
		Blue											0.46	27.0	-
		Green(e-)											1.27	54.0	-
	Hydrogen	Grey	120	8.5	7.6	-253	3	0.017	585	3.5	high	-	1.30	10.8	95
		Blue											2.10	17.5	-
		Green(e-)											5.20	43.3	-
	Bio-diesel		37.2	35.7	1	25	9	N/A	204	N/A	low	-	0.63	16.9	78

* Fuel cost may greatly vary depending on the period and situation. Current unit costs in the Table are quoted from the following sources as of 2021: HFO/MGO [100], LNG [113], methanol [95, 108], ammonia [64, 93], hydrogen (on the basis of generation cost of $60/MWh and water electrolysis investment cost of $1000/kW) [114], biodiesel [115]

According to a study [28], when analyzing the cost required to retrofit a ship with a 10-25 MW engine to one with a dual fuel engine, the cost for LNG case is €1,000/kW, which is approximately three times higher than methanol case (€300/kW), with more time is required for engine conversion. As for methanol, it is known that the cost of installing a bunkering unit with an ordinary capacity fuel is $400K and the cost for bunkering ship construction is $1.5M. On the other hand, in the case of LNG, the terminal construction costs $50M and the bunker barge costs $30M due to the facilities for storing fuel at high pressure and cryogenic temperature. Also, the bunkering and fuel prices appear to be more unstable than methanol (Figure 7-2). Nonetheless, should the present volatility in LNG prices be attributed to shifts in demand driven by the need for alternative fuels, it seems likely that a comparable trend could emerge for methanol in the future.

7.2. Comparison with Hydrogen

- GHG emissions reduction

Regarding hydrogen, there are no greenhouse gas (GHG) emissions in the TtW process. However, in WtW process that spans WtT and TtW processes, the WtW GHG emissions intensity of gray hydrogen is 132 g_{CO2eq}/MJ, indicating that gray hydrogen emits more GHGs than heavy fuel oil. Therefore, using gray hydrogen is ineffective in terms of reducing GHG emissions, and a gradual technology transition strategy to blue and green hydrogen must be followed. In current discussion to be an e-hydrogen at least 70% of reduction of GHG intensity over WtW process is required against the fossil fuel (IMO: 94 g_{CO2eq}/MJ), so the hydrogen fuel that can emit less than 28.2 g_{CO2eq}/MJ is expected to be recognized as green hydrogen.

- Ecological impact and risk

Similar to methanol, hydrogen can be regarded as producing no particulate matter (PM10). Moreover, being a gaseous substance that rapidly evaporates in case of leakage, it poses no water toxicity concerns (Table 7-2).

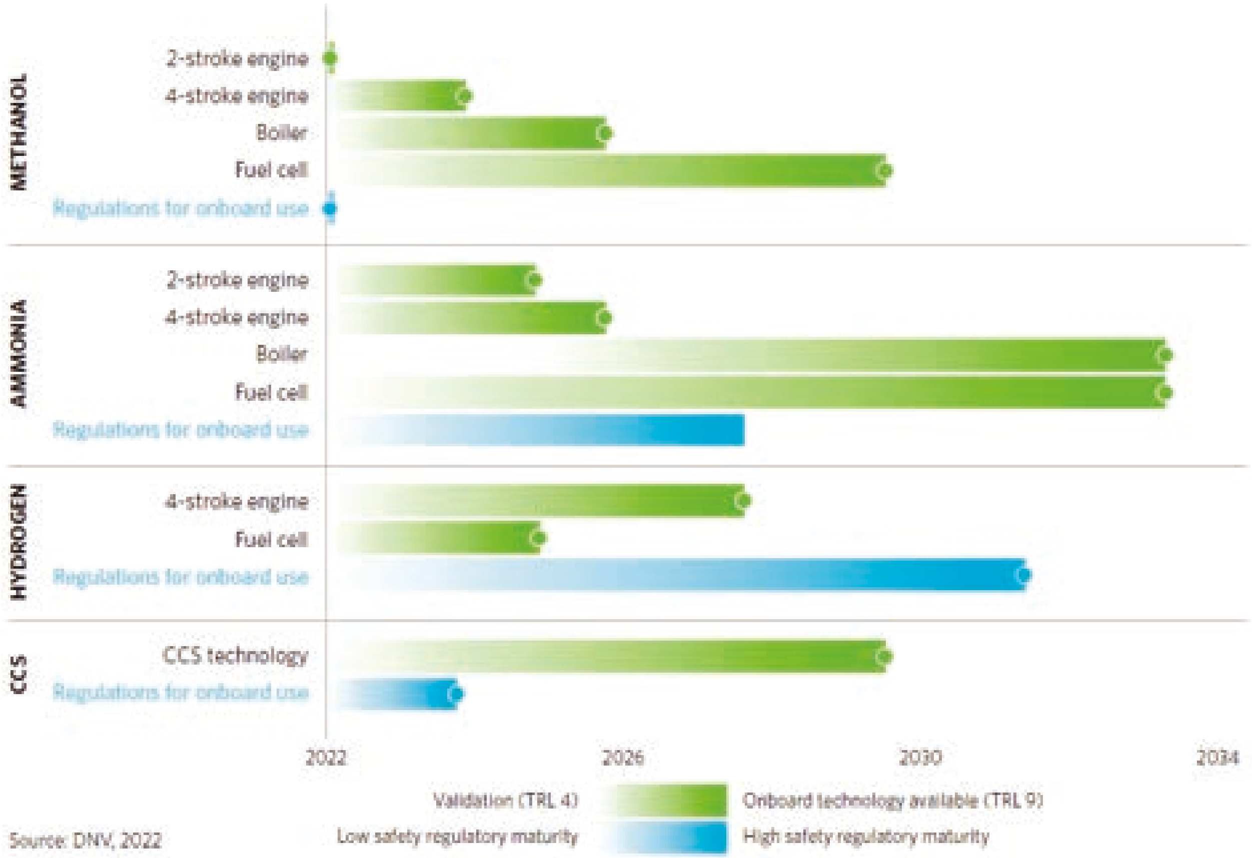
- Availability and technical status

The methanol engine has achieved commercialization at TRL 9. It can be used in gasoline engines without substantial modifications, and can also be applied to diesel engines with pilot fuels. On the contrary, hydrogen's large-scale fuel cell technology for ships is presently at the TRL 3 level. The overall technological maturity of direct combustion engines for hydrogen is low, and a considerable

Methanol has been transported by ship as cargo for a long time and has been industrially applied in various places, so most related regulations have been established.

amount of time is expected to be required to establish relevant regulations (Figure 7-2).

In the case of hydrogen, the energy per unit volume is only 60% to that of methanol, but the required space for cargo handling systems is estimated to be 3 and 7 times larger than that of methanol and HFO respectively. This is because, for hydrogen, additional facilities are required to maintain cryogenic storage temperature of -253℃ and to handle boil-off gas (BOG). (Table 7-2). Furthermore, as large-scale production facilities and bunkering facilities have not yet been established for hydrogen, considerable investment cost and a development time are anticipated.



|Figure 7-2| Expected engine development and regulation establishment scenario for next-generation fuel [99].

- Economic feasibility

As of 2021, the production cost of gray hydrogen is estimated to be around $10.8/GJ [114], though it varies significantly depending on the production regions which is lower than that for of gray methanol ($20.1/GJ) (Table 7-2). The unit cost of blue hydrogen ($17.5/GJ) is also estimated to be lower than that of gray methanol. The cost of green hydrogen ($43.3/GJ) is lower than that of e-methanol ($66/GJ) but higher than that of gray methanol and bio-methanol ($30.0/GJ) (Table 7-2). This is because e-methanol production involves the green hydrogen production process, whereas bio-methanol can be produced from biomass at a relatively lower cost. In other words, blue hydrogen is available for partial reduction of GHG emissions, but bio-methanol may be more advantageous in achieving net zero emissions. This trend may persist for a while as the progress in green hydrogen production and hydrogen engine development are anticipated to be slower compared to other engine technologies. (Figure 7-2), In particular, for hydrogen, high pressure or cryogenic temperature facilities are required for terminals and bunkering systems, so it is expected that considerable cost and time would also be required for establishing infrastructure.

7.3. Comparison with Ammonia

- GHG emissions reduction

The WtW GHG emissions intensity of gray ammonia is 121g_{CO2eq}/MJ, which is 20% higher than that of gray methanol (100.4 gCO2eq/MJ). In the case of methanol, GHGs are emitted mainly during the combustion (TtW) process, but for ammonia, GHGs are mainly emitted during the production and transportation (WtT) process (Table 7-1). Currently, ammonia's TtW GHG emissions intensity are indicated as 0, but it is becauase the evaluation of GHG emissions resulting from combustion of ammonia engines has not yet been completed. There are studies reporting that an excessive amount of N_2O is emitted during the ammonia combustion process, so caution is needed, as the TtW emissions during ammonia combustion may have a non-zero value.The emission of nitrogen oxides during the ammonia combustion is attributed to its narrow flammable range, relatively high minimum ignition energy (8 mJ), and a low flame speed (0.015 m/s) (Table 7-2). To reduce nitrogen oxide generation, ammonia engines basically use spark plugs with high ignition energy or multiple spark plugs. There have been developments of a dedicated engine that injects pilot fuel, or a dual fuel engine that uses a mixture of 20~40wt% of diesel, but since both methods require additional use of fuels, GHG emissions from pilot fuels are inevitable [109]. NOx from the combustion process, can be reduced by applying a nitrogen oxide post-treatment device such as selective catalyst reduction (SCR).

- Ecological impact and risk

Ammonia exhibits a notably low LC50 (50% fatality rate) value of 0.07 mg/L, reflecting its low tolerance threshold for aquatic toxicity, so even a minor leakage is likely to exert a considerable adverse impact on the aquatic ecosystem (Table 7-1). This figure is much smaller compared to methanol (15,400 mg/L) HFO (79 mg/L) or MGO (8 mg/L). Furthermore, as it is highly toxic to the human body ships using ammonia fuel must have safety equipment onboard to reduce risks, as mentioned in Chapter 5.

Ammonia requires difficult conditions for combustion and having a high flash point of 132℃, the risk of fire or explosion can be considered relatively lower than methanol that has a risk of being ignited at atmospheric temperature. However, since the kinematic viscosity of ammonia is 0.2 cSt at 20℃, which is approximately one-third of that of methanol (0.7 cSt), extent of damage spread could be greater than methanol.

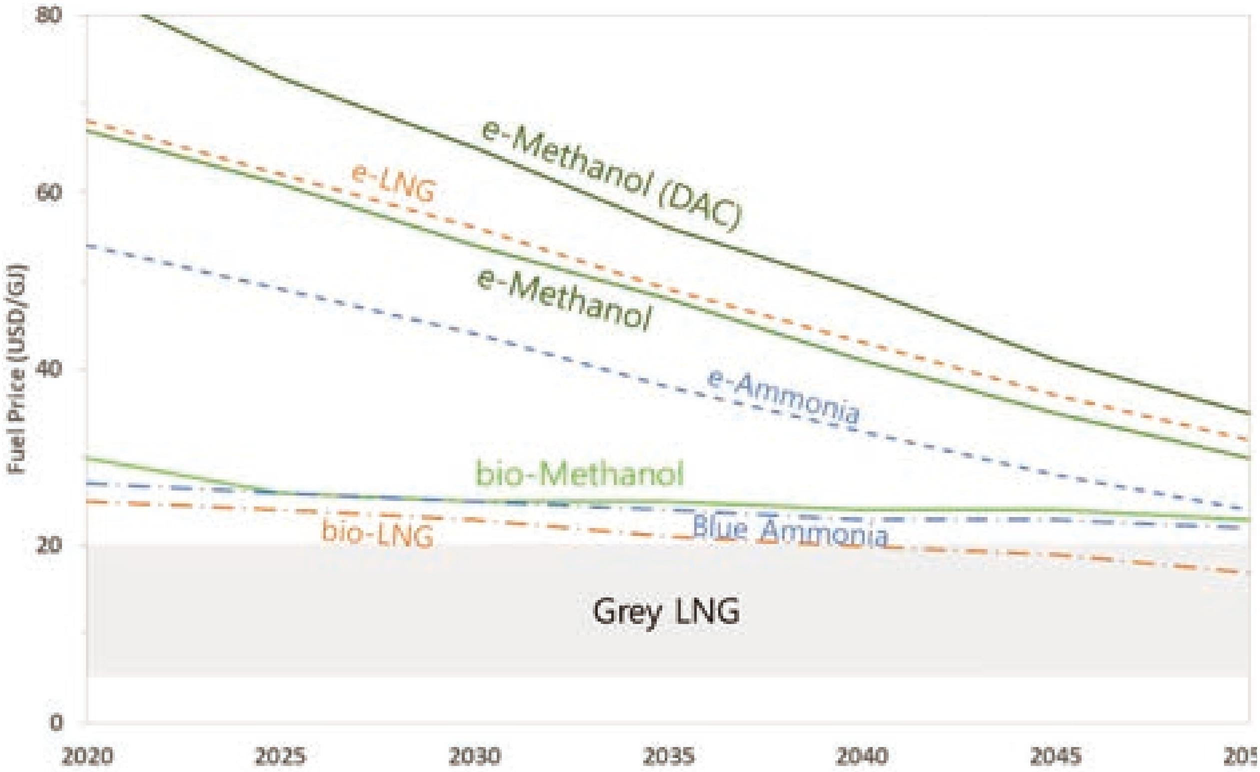
- Availability and technical status

Since ammonia has been used as a fertilizer for a long time, it has a large-scale global supply chain and a 1.5 times larger production scale to methanol (Table 7-2). However, the storage temperature is low (around -34℃) at atmoshperic pressure, and the energy per unit volume is 15% less than methanol. Because insulation and cargo handling systems are required, the required space for cargo handling systems is approximately four times that of HFO and twice that of methanol. As of now, fuel terminals and bunkering infrastructure are rarely built. The engine for ammonia fuel is under development, which has not yet been commercialized, so its development level is still at TRL 6-7 level, which is lower than that of methanol (TRL 9). The environmental assessment of toxicity of ammonia is expected to be completed around 2028 (Figure 7-3), so the construction of ammonia fuel infrastructure may take more time than expected.

- Economic feasibility

According to previous studies [96, 100], based on the 11,000kW engine for an 82,000 DWT ship, the cost of ammonia engine is estimated as around $1400/kW, approximately 1.8 times that of methanol ($800/kW). Moreover, unlike methanol, there have been no instances of utilizing ammonia through the modification of existing engines. Concerning the construction costs for terminals and bunker barges, higher expenses are anticipated for ammonia compared to methanol, given that ammonia needs to be stored at -34℃ due to its toxic nature.

In terms of fuel costs, gray ammonia is priced at approximately $13.4/GJ, forming a price range that is around 30% lower than gray methanol. Blue ammonia ($27/GJ) is cheaper than bio-methanol ($30/GJ), but considering the costs required for long-distance transport, it is expected to reach a similar level. Green ammonia ($54.0/GJ) is more expensive than bio-methanol ($30/GJ) but falls in an intermediate position, being cheaper than e-methanol ($66/GJ) (Figure 7-3). Given the significant cost variations of e-methanol based on raw materials and regions, it is anticipated that e-ammonia and e-methanol will enter into competition once ammonia engines are commercialized. The current high production cost of e-ammonia is due to the high production cost of green hydrogen and high energy consumption required for hydrogen-ammonia conversion. The value could be lowered to $25-30/GJ according to the higher production technology readiness, and will be competitive with bio-methanol and e-methanol in the future.



|Figure 7-3| Fuel price forecast for bio-/e-LNG, blue/e-ammonia, and bio-/e-methanol [64, 93-95, 113].

Reference

[1] NOAA. (2023). Climate Change: Atmospheric Carbon Dioxide. Retrieved July 13, 2023 from https://www.climate.gov/news-features/understanding-climate/climate-change-atmospheric-carbon-dioxide

[2] NASA Earth Observatory (2020). World of Change: Global Temperatures. Retrieved July 13, 2023 from https://earthobservatory.nasa.gov/world-of-change/global-temperatures

[3] IPCC Sixth Assessment Report (2021). Figure SPM.1 in IPCC, 2021: Summary for Policymakers. In: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY,USA, pp. 3–32, doi: 10.1017/9781009157896.001].

[4] United Nations Climate Change (2022). COP27 Reaches Breakthrough Agreement on New "Loss and Damage" Fund for Vulnerable Countries. Retrieved July 13, 2023 from https://unfccc.int/news/cop27-reaches-breakthrough-agreement-on-new-loss-and-damage-fund-for-vulnerable-countries

[5] IMO. (2021). Addressing climate change - a decade of action to cut GHG emissions from shipping. Retrieved July 11, 2023 from https://imo-newsroom.prgloo.com/resources/qeyk2-uxspi-9m5qy-ilbbo-tk2u5

[6] Bilgili, L. (2021). Comparative assessment of alternative marine fuels in life cycle perspective. Renewable and Sustainable Energy Reviews, 144, 110985.

[7] IMO. (2021). Fourth IMO GHG study 2020.

[8] IMO. (2021). Guidelines on life cycle GHG intensity of marine fuels (LCA Guidelines). Retrieved July 11, 2023 from https://www.imo.org/en/OurWork/Environment/Pages /Lifecycle-GHG---carbon-intensity-guidelines.aspx

[9] IMO. (2014). Third IMO greenhouse gas study.

[10] Sawin, J. L., Martinot, E., Barnes, D., McCrone, A., Roussell, J., Sims, R., Sonntag-O'Brien, V., Adib, R., Skeen, J., & Musolino, E. (2013). renewables 2011-Global status report.

[11] Sternberg, A., & Bardow, A. (2015). Power-to-What?-Environmental assessment of energy storage

systems. Energy & Environmental Science, 8(2), 389-400.
[12] IRENA. (2022). Global hydrogen trade to meet the 1.5°C climate goal: Part I - Trade outlook for 2050 and way forward, International Renewable Energy Agency, Abu Dhabi.
[13] IRENA. (2022). World Energy Transitions Outlook 2022: 1.5°C Pathway, Iternational Renewable Energy Agency, Abu Dhabi.
[14] Viscardi, R., Bassano, C., Nigliaccio, G., & Deiana, P. (2021). The potential of E-fuels as future fuels. In.
[15] Dieterich, V., Buttler, A., Hanel, A., Spliethoff, H., & Fendt, S. (2020). Power-to-liquid via synthesis of methanol, DME or Fischer-Tropsch-fuels: a review. Energy & Environmental Science, 13(10), 3207-3252.
[16] Ampah, J. D., Yusuf, A. A., Afrane, S., Jin, C., & Liu, H. (2021). Reviewing two decades of cleaner alternative marine fuels: Towards IMO's decarbonization of the maritime transport sector. Journal of Cleaner Production, 320, 128871.
[17] Brynolf, S., Fridell, E., & Andersson, K. (2014). Environmental assessment of marine fuels: liquefied natural gas, liquefied biogas, methanol and bio-methanol. Journal of Cleaner Production, 74, 86-95.
[18] Xing, H., Stuart, C., Spence, S., & Chen, H. (2021). Alternative fuel options for low carbon maritime transportation: Pathways to 2050. Journal of Cleaner Production, 297, 126651.
[19] Brooks, M. R., & Crowl, D. A. (2007). Flammability envelopes for methanol, ethanol, acetonitrile and toluene. Journal of Loss Prevention in the Process Industries, 20(2), 144-150.
[20] Gilbert, P., Walsh, C., Traut, M., Kesieme, U., Pazouki, K., & Murphy, A. (2018). Assessment of full life-cycle air emissions of alternative shipping fuels. Journal of Cleaner Production, 172, 855-866.
[21] Global Maritime Forum. (2021). The Next Wave: Green Corridors.
[22] Jamrozik, A. (2017). The effect of the alcohol content in the fuel mixture on the performance and emissions of a direct injection diesel engine fueled with diesel-methanol and diesel-ethanol blends. Energy Conversion and Management, 148, 461-476.
[23] Sayin, C. (2010). Engine performance and exhaust gas emissions of methanol and ethanol-diesel blends. Fuel, 89(11), 3410-3415.
[24] 해양수산부. (2021). 액화천연가스(LNG)를 넘어 메탄올 연료 추진선박이 온다 https://www.mof.go.kr/synap/view.do?fn=MOF_ARTICLE_39150_2021061717a17caeb4c550&fd=202307
[25] Radonja, R., Bebić, D., & Glujić, D. (2019). Methanol and ethanol as alternative fuels for shipping. Promet-Traffic&Transportation, 31(3), 321-327.
[26] Marquez, C. (2023). Marine Methanol: Future-Proof Shipping Fuel.

[27] IRENA. (2022). Hydrogen. Retrieved July 16, 2023 from https://www.irena.org/Energy-Transition/Technology/Hydrogen

[28] Andersson, K., & Salazar, C. M. (2015). Methanol as a marine fuel report. FCBI energy, 1-46.

[29] IRENA & Methanol Institute (2021). Innovation Outlook : Renewable Methanol, International Renewable Energy Agency, Abu Dhabi.

[30] Abdalla, N., Bürck, S., Fehrenbach, H., Köppen, S., & Staigl, T. J. (2022). Biomethane in Europe. https://www.ifeu.de/fileadmin/uploads/ifeu_ECF_biomethane_EU_final_01.pdf

[31] Consoli, C. (2019). Bioenergy and carbon capture and storage, 2019 perspective. https://www.globalccsinstitute.com/wp-content/uploads/2020/04/BIOENERGY-AND-CARBON-CAPTURE-AND-STORAGE_Perspective_New-Template.pdf

[32] Maersk. (2020). Leading Danish companies join forces on an ambitious sustainable fuel project. Retrieved July 18, 2023 from https://www.maersk.com/news/articles/2020/05/26/leading-danish-companies-join-forces-on-an-ambitious-sustainable-fuel-project

[33] Olsson, O., Tynjälä, T., Bang, C., & Thrän, D. (2020). Deployment of BECCS/U - technologies, supply chain setup & policy options. https://www.ieabioenergy.com/wp-content/uploads/2020/06/BECCUS-Webinar-Slide-OO20200616-final.pdf

[34] Transport & Environment (2022). FuelEU Maritime: T&E analysis and recommendations. How to drive the uptake of sustainable fuels in shipping.

[35] IMO. (2015). Resolution MSC.391(95), Adoption of the International Code of Safety for Ships Using Gases or Other Low-Flashpoint Fuels (IGF CODE).

[36] IMO. (2015). Resolution MSC.392(95), Amendments to the international convention for the safety of life at sea, 1974, as amended.

[37] Yao, C., Cheung, C. S., Cheng, C., Wang, Y., Chan, T. L., & Lee, S. C. (2008). Effect of diesel/methanol compound combustion on diesel engine combustion and emissions. Energy conversion and management, 49(6), 1696-1704.

[38] René, S.L. (2017). The 2-stroke ME-LGIM. Methanol Vessel Fuel Blending. https://www.methanol.org/wp-content/uploads/2017/06/Rene-Laursen-Methanol-Vessel-Fuel-Blending-.pdf

[39] Methanol Institute. (2023). Marine Methanol: Future-Proof Shipping Fuel

[40] ABC. (2023). Carbon neutrality through simplicity: discover ABC's dual fuel methanol engines [Press release]. https://www.abc-engines.com/en/news/dzd-meoh-engines

[41] HD HHI. (2022). Hyundai Engine & Machinery keeps leading in Methanol duel fuel engines [Press re-

lease]. https://www.hyundai-engine.com/en/Media/newsdetail/381
[42] HD HHI. (2022). HHI-EMD, The Eco-friendly Methanol Dual Fuel HiMSEN Engine(H32DF-LM) Development [Press release]. https://www.hyundai-engine.com/en/Media/newsdetail/401
[43] HD HHI. (2023). HHI-EMD, Methanol Dual Fuel HiMSEN Engine FAT [Press release]. https://www.hyundai-engine.com/en/Media/newsdetail/406
[44] Waterfront Shipping. (2016, Apr 11). Industry Welcomes World's First Ocean-Going Vessels Capable of Running on Methanol. https://www.waterfront-shipping.com/news/2016/04/industry-welcomes-worlds-first-ocean-going-vessels-capable-running-methanol
[45] Cha, S. (2023, May 25). Navigating the future fuel outlook for large merchant marine vessels. Seizing opportunities for green shipping in Asia and the Pacific. https://www.imo.org/en/About/Events/Pages/Seizing-Opportunities-for-Green-Shipping.aspx
[46] Hoppe, J. (2021, Nov 29). MAN Energy Solutions Upgrading Four-Stroke Engines for Green Future-Fuels [Press release]. https://www.man-es.com/company/press-releases/press-details/2021/11/29man-energy-solutions-upgrading-four-stroke-engines-for-green-future-fuels
[47] Søholt, N. (2023, Mar 13). Methanol-Ready 32/44CR Wins RINA Approval [Press release]. https://www.man-es.com/company/press-releases/press-details/2023/03/13/methanol-ready-32-44cr-wins-rina-approval
[48] MAN ES. (2021). Methanol-fueled MAN B&W LGIM Engine.
[49] WÄRTSILÄ. (2022). Wärtsilä 32 methanol - The power to reach carbon-neutral [Webinar]. https://www.wartsila.com/insights/webinar/wartsila-32-methanol-the-power-to-reach-carbon-neutral
[50] WÄRTSILÄ. (2023). Wärtsilä Future Fuel Technology & Product Development - Decarbonising the Maritime Industry through the Uptake of Methanol and Ammonia. https://ingenierosnavales.com/wp-content/uploads/2023/03/Wartsila-New-Fuel-Roadmap-Comms-2023_02.pdf
[51] WÄRTSILÄ. https://www.wartsila.com/insights/article/methanol-fuel-for-thought-in-our-deep-dive-q-a#methanol-and-compliance
[52] MESD. (2021). Methanol as a Marine Fuel - Availability and Sea Trial Considerations
[53] Thurman, A. (2023). Methanol as marine fuel - is it the solution you are looking for?.
[54] WÄRTSILÄ. (2023). THE WÄRTSILÄ 32 METHANOL ENGINE [Brochure].
[55] WÄRTSILÄ. (2023). WÄRTSILÄ 32 METHANOL - Product Guide.
[56] Garcia, A. (2021). WinGD sets development timeframe for methanol and ammonia engines [Press re-

lease]. https://www.wingd.com/en/news-media/press-releases/wingd-sets-development-time-frame-for-methanol-and-ammonia-engines/

[57] WinGD. (2023). WinGD and HSD Engine advance methanol engine collaboration [Press release]. https://www.wingd.com/en/news-media/wingd-in-the-news/wingd-and-hsd-engine-advance-methanol-engine-collaboration-en/

[58] Garcia, A. (2023). WinGD to deliver methanol engines for COSCO SHIPPING Lines container vessels [Press release]. https://www.wingd.com/en/news-media/press-releases/wingd-to-deliver-methanol-engines-for-cosco-shipping-lines-container-vessels/

[59] The Maritime Executive. (2023). Evergreen Orders 24 Methanol-Fueled Ships at a Cost of Nearly $5 Billion. https://maritime-executive.com/article/evergreen-orders-24-methanol-fueled-ships-at-a-cost-of-nearly-5-billion

[60] The Maritime Executive. (2023). Evergreen Orders 24 Methanol-Fueled Ships at a Cost of Nearly $5 Billion. https://maritime-executive.com/article/evergreen-orders-24-methanol-fueled-ships-at-a-cost-of-nearly-5-billion

[61] MMMC. (2022). Preparing Container Vessels for Conversion to Green Fuels. https://www.zerocarbonshipping.com/publications/preparing-container-vessels-for-conversion-to-green-fuels-2/

[62] Wissner, N., Healy, S., Cames, M., & Sutter, J. (2023). Methanol as a marine fuel.

[63] Merk, O., Kirstein, L., & Halim, R. (2018). Decarbonising Maritime Transport-Pathways to zero-carbon shipping by 2035.

[64] Korean Register. (2019). Forecasting the Alternative Marine Fuel - Ammonia.

[65] Stolz, B., Held, M., Georges, G., & Boulouchos, K. (2022). Techno-economic analysis of renewable fuels for ships carrying bulk cargo in Europe. Nature Energy, 7(2), 203-212.

[66] FCBI energy (2015). Methanol as a marine fuel report.

[67] Harmsen, J. (2021, Feb 19). Green Maritime Methanol. Towards a zero emission shipping industry.

[68] Marine Service Noord. (n.d.). Case Study MV Eemsborg. https://marine-service-noord.com/en/products/alternative-fuels-and-technologies/methanol/case-study-mv-eemsborg/

[69] Snyder, J. (2023). 2022 shipbuilding volumes slide, but order value tops US$124.3Bn. Riviera Maritime Media. https://www.rivieramm.com/news-content-hub/2022-shipbuilding-volumes-slide-but-order-value-tops-us1243bn-75094

[70] Rasmussen, P. D. (2022). A.P. Moller - Maersk continues green transformation with six additional large container vessels. https://www.maersk.com/news/articles/2022/10/05/maersk-continues-green-

transformation

[71] Bahtic, F. (2023). Maersk: World's 1st containership operating on green methanol delivered. Offshore energy. https://www.offshore-energy.biz/maersk-worlds-1st-containership-operating-on-green-methanol-delivered/

[72] Schuler, M. (2022). Maersk Exercises Options for Four More Methanol-Powered Containerships. gCaptain - Maritime News. https://gcaptain.com/maersk-exercises-options-for-four-more-methanol-powered-containerships/

[73] Linnet, M. E. (2023). Maersk orders six methanol powered vessels [Press release]. https://www.maersk.com/news/articles/2023/06/26/maersk-orders-six-methanol-powered-vessels

[74] LNG Prime. (2022). CMA CGM orders six methanol-fueled containerships in China. https://lngprime.com/asia/cma-cgm-orders-six-methanol-fueled-containerships-in-china/58880/

[75] Li, M. (2023). CMA CGM books another dozen 13,000 teu methanol-powered ships. The Loadstar Media. https://theloadstar.com/cma-cgm-books-another-dozen-13000-teu-methanol-powered-ships/

[76] Gronda, L. (2023). CMA CGM in $3bn methanol, LNG ship deal. Argus Media. https://www.argusmedia.com/en/news/2438212-cma-cgm-in-3bn-methanol-lng-ship-deal

[77] Ship & Bunker News. (2023). CMA CGM Moves Ahead of Maersk on Methanol Powered Ship Orders. https://shipandbunker.com/news/world/740116-cma-cgm-moves-ahead-of-maersk-on-methanol-powered-ship-orders

[78] Ajdin, A. (2022). COSCO orders twelve methanol-fuelled 24,000 teu ships. Splash 247. https://splash247.com/cosco-orders-twelve-methanol-fuelled-24000-teu-ships/

[79] Chambers, S. (2023). COSCO orders four 16,000 teu ships. Splash 247. https://splash247.com/cosco-orders-four-16000-teu-ships/

[80] Chambers, S. (2023). HMM orders nine methanol-fuelled boxships. https://splash247.com/hmm-orders-nine-methanol-fuelled-boxships/

[81] The Maritime Executive. (2022, Mar 11). Japanese Alliance to Develop First Domestic Methanol-Fueled Tanker. https://maritime-executive.com/article/japanese-alliance-to-develop-first-domestic-methanol-fueled-tanker

[82] Occupational Safety and Health Research Institute. (2023). http://msds.kosha.or.kr/MSDSInfo/kcic/chemlList.do?pageIndex=202

[83] Bailera, M. (2017). Power to Gas projects review: Lab, pilot and demo plants for storing renewable

energy and CO_2. Renewable and Sustainable Energy Reviews, 292-312.

[84] Ming, L., & Chen, L. (2021). Methanol as a Marine Fuel: Availability and Sea Trial Considerations.

[85] Svanberg, M., & Ellis, J. (2018). Renewable methanol as a fuel for the shipping industry. Renewable and Sustainable Energy Reviews, 1217-1228.

[86] Wu, J.S. Wu, J.Z. (2021). Research status and prospect of methanol as alternative fuel for diesel engines. Energy Conservation Technology, 1, 9-14.

[87] Liu, R. (2018). A review of research methods for risk assessment. Gansu Science and Technology Frontiers, 9, 61-63.

[88] Methanol Market Services Asia. (n.d.). Methanol Price and Supply/Demand.

[89] Olah, G. A., Goeppert, A., & Prakash, G. K. S. (2018). Beyond oil and gas: the methanol economy. John Wiley & Sons.

[90] SGS INSPIRE Team. (2020). Methanol: Properties and Uses.

[91] Dolan, G. (2019). Overview of Global Methanol Fuel Blending. https://www.methanol.org/wp-content/uploads/2019/02/4.-Greg-Dolan-Overview-of-Global-Methanol-Fuel-Blending.pdf

[92] Intratec. (n.d.). Primary Commodity Prices: Methanol. Retrieved July 10, 2023, from https://www.intratec.us/user/products/primary-commodity-prices#alcohols-organic-acids

[93] MMMC. (2022). Ammonia as a marine fuel: Prospects for the shipping industry. https://www.zerocarbonshipping.com/publications/ammonia-documentation-for-navigate-1-0/

[94] MMMC. (2022). LNG and methane-based marine fuels: Prospects for the shipping industry. https://www.zerocarbonshipping.com/publications/methane-documentation-for-navigate-1-0/

[95] MMMC. (2022). Methanol as a marine fuel:Prospects for the shipping industry. https://www.zerocarbonshipping.com/publications/methanol-documentation-for-navigate-1-0/

[96] Lloyd's Register. (2020). Introduction to Methanol Bunkering: Technical Reference. http://www.lr.org/entities

[97] Wang, Y., & Wright, L. A. (2021). A Comparative Review of Alternative Fuels for the Maritime Sector: Economic, Technology, and Policy Challenges for Clean Energy Implementation. World, 2(4), 456-481. https://doi.org/10.3390/world2040029

[98] Comer, B., & Osipova, L. (2021). Accounting for well-to-wake carbon dioxide equivalent emissions in maritime transportation climate policies.

[99] DNV GL (2018). Assessment of Selected Ternative Fuels and Technologies.

[100] Lindstad, E., Lagemann, B., Rialland, A., Gamlem, G. M., & Valland, A. (2021). Reduction of maritime

GHG emissions and the potential role of E-fuels. Transportation Research Part D: Transport and Environment, 101(November), 103075. https://doi.org/10.1016/j.trd.2021.103075

[101] Djermouni, M., & Ouadha, A. (2023). Thermodynamic analysis of methanol, ammonia, and hydrogen as alternative fuels in HCCI engines. International Journal of Thermofluids, 19(May), 100372.

[102] van Lieshout, P. S., de Jonge, V., Verbeek, R., Vredeveldt, A. W., & Finner, S. (2020). Green Maritime Methanol: WP3 factsheet and comparison with diesel and LNG.

[103] TNO (2020). Unconventional bunker fuels, a safety comparison.

[104] ADDFUEL. (2017). Marine Fuel Oil (MGO & HFO) and FCC Additive Technical Analysis.

[105] MESD. (2021). Methanol as a Marine Fuel - Availability and Sea Trial Considerations

[106] Hyundai Heavy Industries. (2023). Decarbonization. http://www.hyundai-engine.com/ko/aboutus/Decarboni zation.

[107] Sharifian, R., Wagterveld, R. M., Digdaya, I. A., Xiang, C., & Vermaas, D. A. (2021). Electrochemical carbon dioxide capture to close the carbon cycle. Energy & Environmental Science, 14(2), 781-814. https://doi.org/10.1039/D0EE03382K

[108] Methanex. (2023). Investor Presentation. https://www.methanex.com/wp-content/uploads/MEOH-Investor-Presentation-May-2023.pdf

[109] Kim, D. H., Lee, K.-Y., & Kwon, D. W. (2022). Trends of Cleaner Alternative Marine Fuels and Exhaust Emission Abatement Technology for Carbon Neutrality. Korean Industrial Chemistry News, 25(2), 8-27.

[110] Solakivi, T., Paimander, A., & Ojala, L. (2022). Cost competitiveness of alternative maritime fuels in the new regulatory framework. Transportation Research Part D: Transport and Environment, 113(May), 103500. https://doi.org/10.1016/j.trd.2022.103500

[111] Alfa Laval, Hanfia, Haldor Topsøe, Vestas, & Siemens Gamesa. (2020). Ammonfuel - An Industrial View of Ammonia as a Marine Fuel.

[112] OEKO. (2021). Ammonia as a marine fuel: Risks and perspectives.

[113] FRED (2021), Global price of LNG Asia

[114] Goldman Sachs (2022), Carbonomics: The clean hydrogen revolution

[115] Bureau Veritas. (2022). Alternative Fuels Outlook for Shipping: An Overview of Alternative Fuels From a Well-To-Wake Perspective.

Report Writing

|Korean Register (KR)|

Lead author Changwook Kim, Sangick Lee

Co-authors Choungho Choung

|Seoul National University|

Lead author Youngsub Lim

Co-authors Heechang Son, Geonwoo Jeong

|Korea Institute of Science and Technology (KIST)|

Co-authors Changsoo Kim, Damdae Park

Research partners:

KOREAN REGISTER   Korea Institute of Science and Technology


KOREAN REGISTER

KOREAN REGISTER

36, Myeongji Oceancity 9-Ro, Gangseo-Gu, Busan, Republic of Korea, 46762 **www.krs.co.kr**

KR-RND-DECB-INF-004