KR-RND-DECB-INF-002

Ammonia Outlook Report: Setting Course for a Zero-Carbon Marine Fuel

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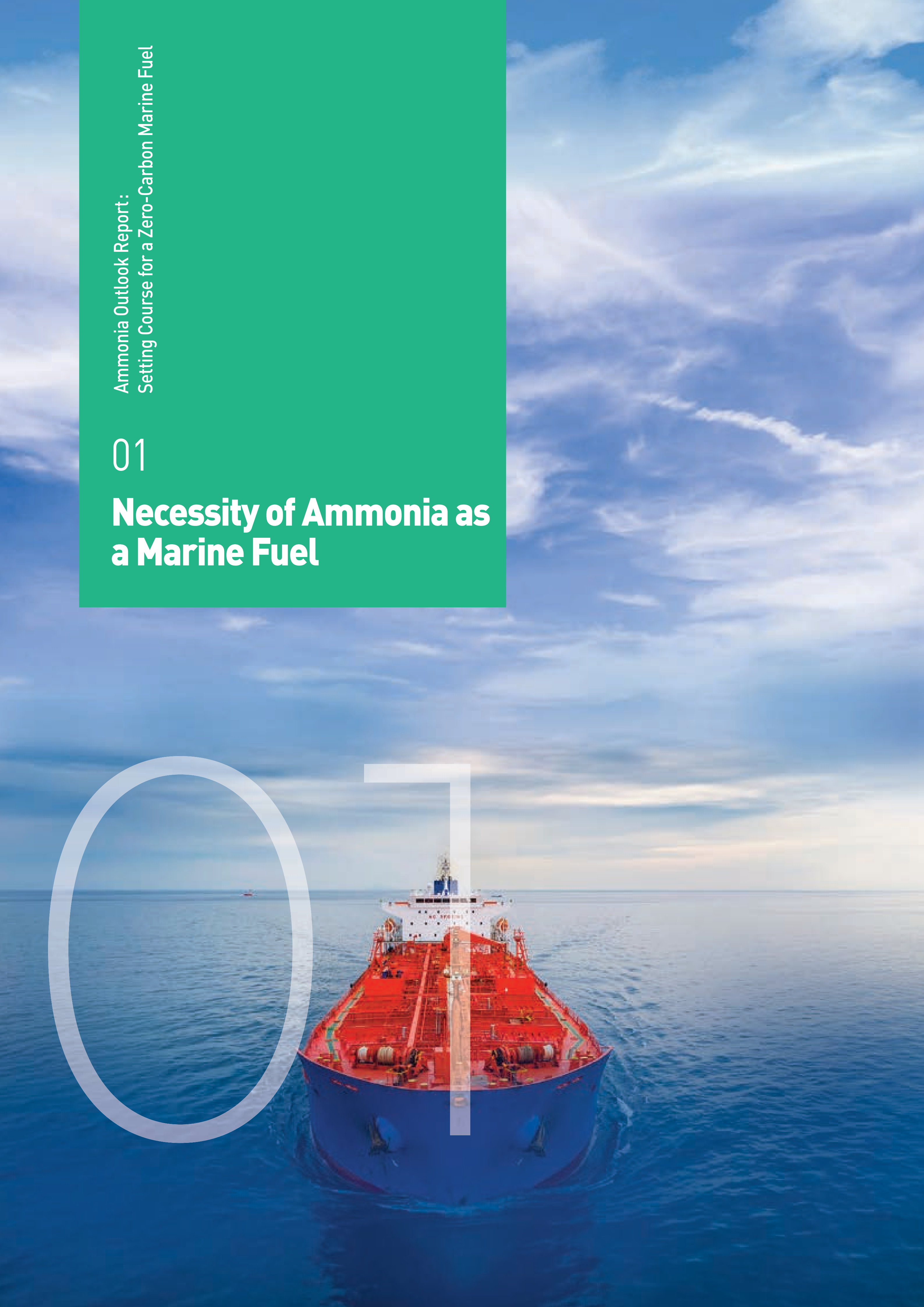
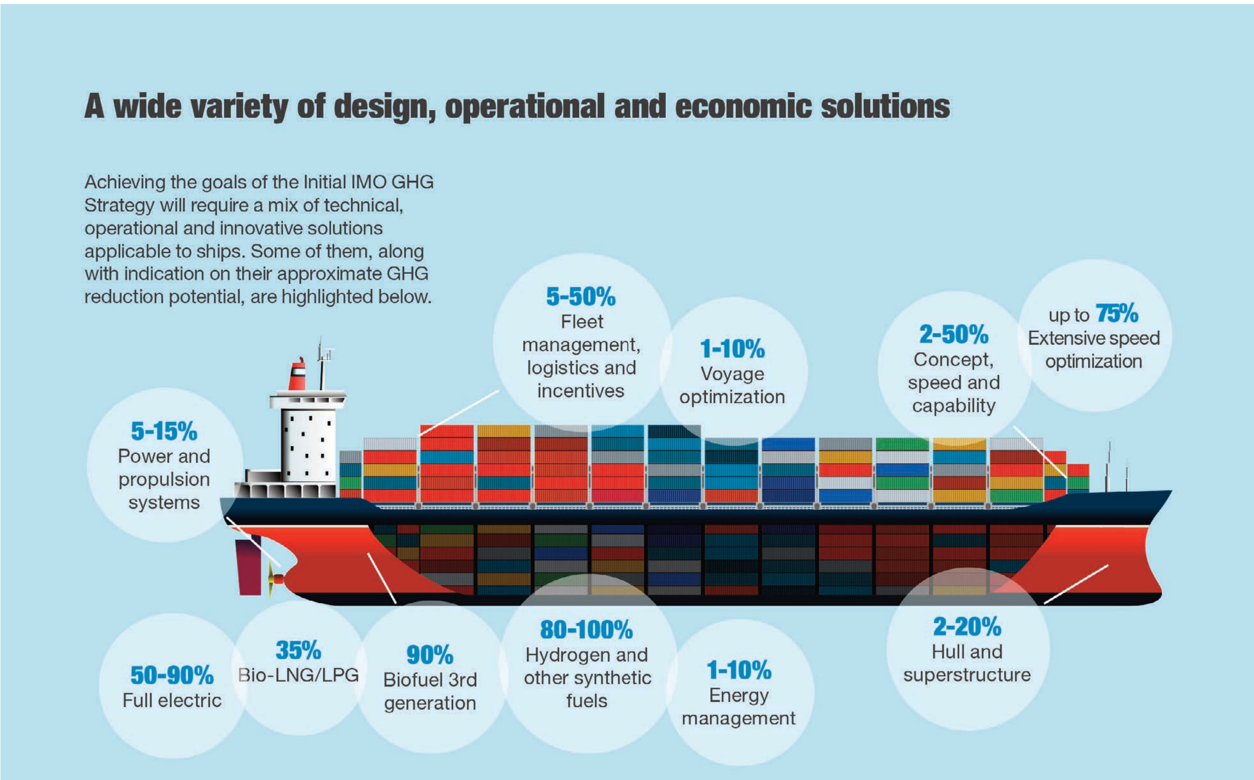
Necessity of Ammonia as a Marine Fuel



In response to the mounting threats of climate change issues such as rising sea levels, heat waves, and water shortages caused by global warming, 195 countries worldwide including South Korea, have adopted the Paris Climate Agreement (2015) and committed to reduce greenhouse gas (GHG) emissions. The shipping sector accounts for approximately 2.89% of global CO_2 emissions. Accordingly, the International Maritime Organization (IMO) adopted the Initial IMO GHG Strategy in 2018 with the goal of carbon-free shipping by completely phasing out GHG emissions from the shipping sector in this century and the first target is to cut GHG emissions by 50% by 2050 based on its level in 2008.

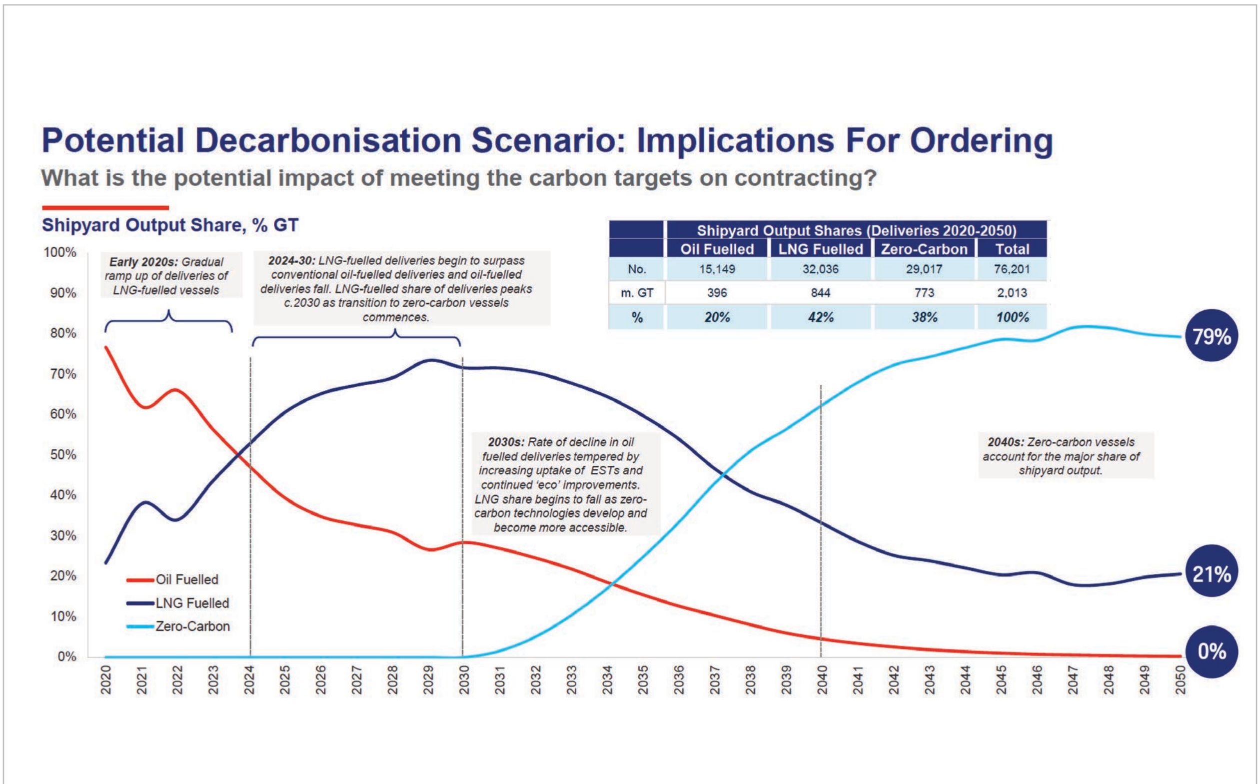
This Initial IMO Strategy will be confirmed and finalized in 2023. However, several countries, which are predominantly from Europe, have proposed that net-zero shipping emissions should be achieved by 2050, and not by the end of this century; therefore, even more stringent regulation of GHG emissions is expected. Moreover, the European Union (EU) has pushed for the inclusion of the shipping sector into the Emission Trading Scheme (ETS) by 2024 through "Fit for 55," a package of legislative proposals, and established the new FuelEU Maritime regulation to mandate the use of sustainable marine fuel, leading to the implementation of tighter regulations, which will further pressurize the IMO. Apart from the transnational regulations pertaining to GHG emissions such as those of the IMO and EU, shippers, charters, and financial institutions have also established GHG emission



|Fig. 1-1| Strategic solutions for implementing the greenhouse gas (GHG) emission control specified by the International Maritime Organization[1]

limits by imposing penalties for achieving environmental, social, and governance metrics; consequently, the reduction of shipping emissions is vital for the survival of shipping companies. To conform to increasingly stringent regulations of the IMO and EU pertaining to GHG emissions, a variety of measures are required, including technical measures such as speed reduction, hull form improvement, low-friction hull coating, wind-assisted propulsion, air lubrication systems, waste heat recovery systems, and onboard CO_2 capture systems and ship operational measures such as routing optimization, speed optimization, ship trim optimization, optimized fleet management, optimization of cargo loading/unloading operations at ports, and use of onshore power supply with the aim of reducing fuel consumption. However, for ultimate accomplishment of the decarbonization target, a transition to sustainable zero-carbon fuels is necessary.

According to the shipyard deliveries forecast scenario[2] presented by Clarkson Research (fuel types are categorized into zero-carbon fuels, liquefied natural gas (LNG), and oil), the share of LNG-fueled vessels is expected to quickly surpass that of fuel oil (FO) to peak in 2030, and zero-carbon fuels are expected to increase their share rapidly from 2030. Moreover, it is expected that, by 2050, conventional fossil fuels will no longer be used and zero-carbon vessels will account for the major share in the shipyard output. These scenarios were developed based on the Initial IMO GHG Strategy, which aims to reduce GHG emissions by 50% by 2050, and if

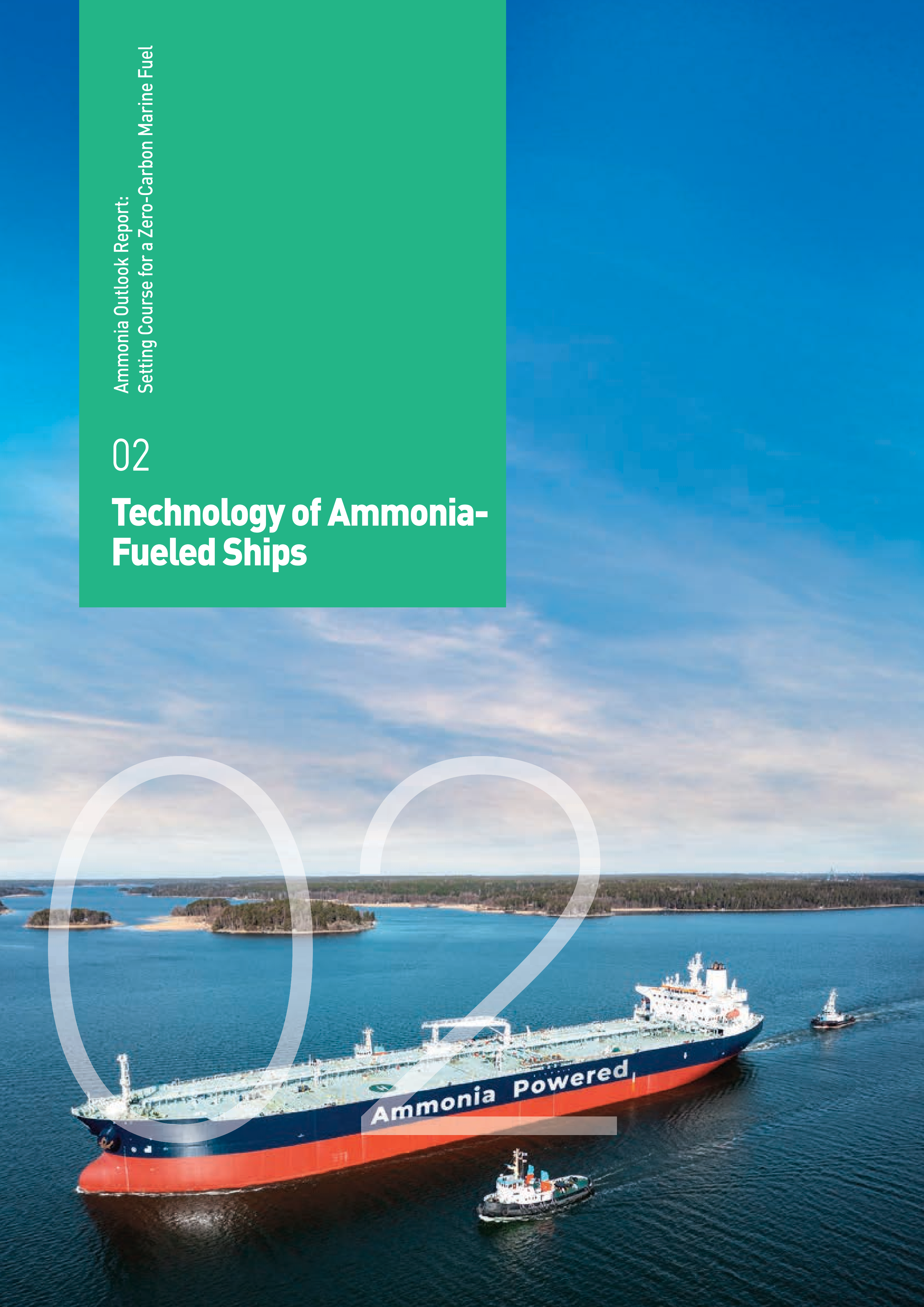


|Fig. 1-2| Scenario of shipyard deliveries as forecast by Clarksons Research[2]

a more ambitious target is finalized in 2023, the use of zero-carbon fuels will begin even earlier, taking the center stage as the major marine fuel. Alternative fuels for ships that can replace the conventional FOs may include LNG, ammonia, methanol, and hydrogen. In the case of ammonia, approximately 180 million tons (MT) of gray ammonia are produced and transported annually, indicating that the port infrastructure is already well established for this fuel. Moreover, as a large amount of hydrogen is required in industries such as power generation, automobiles, and steel manufacturing to fulfill the state-specific Nationally Determined Contribution targets, countries such as China, South Korea, and Japan must import a large amount of blue ammonia, which is reformed from fossil fuels such as natural gas, or green ammonia, which is produced using renewable energy that is imported from foreign countries. Therefore, as the infrastructure for mass production is being developed, ammonia is highly likely to position itself as the commonly used marine fuel with reduced price and ease of supply. However, there are still uncertainties in the related technological developments such as the development of ammonia-fueled engines, safety issues due to the toxicity of ammonia, uncertainties in the production and bunkering of green/blue ammonia, as well as in IMO regulations such as Energy Efficiency Design Index, Carbon Intensity Indicator, and carbon tax; moreover, the comparison of the economic feasibility of ammonia with that of other alternative fuels such as LNG or methanol is rather complex and challenging. Nevertheless, through analyses of the technical characteristics, risk factors, mass production potential, bunkering infrastructure, etc., and through evaluation in comparison with other alternative fuels through various information and assumptions that can be predicted in the current situation, examining the potential and economic feasibility of ammonia as a marine fuel will provide highly useful data for the establishment of fleet development plans for shipping companies in the future. In the case of compressed hydrogen, the energy density is significantly low; therefore, liquefied hydrogen (LH2) is appropriate for ocean-going vessels. However, LH2 is not covered in this report because it requires the development of core technologies such as cargo containment systems, cargo process systems, and large-capacity fuel cells that are suitable for a cryogenic temperature of -253 ℃ as prerequisites.

02

Technology of Ammonia-Fueled Ships



2.1 Fuel Properties of Ammonia

Ammonia is a chemical compound composed of nitrogen and hydrogen and has attracted recent attention as a zero-carbon fuel candidate because it does not emit CO_2 in the combustion process. Because ammonia is liquefied at -33 ℃ under atmospheric pressure, low-pressure tanks in a refrigerated state can be used for its storage; thus, the design and manufacturing of ammonia storage tanks are relatively easy. Moreover, technologies of mass production, transport, and handling of ammonia have already reached a high level of maturity, which is another advantage.

[Table 2-1] Fuel Properties of Ammonia

Category	Description
Chemical formula	NH_3
Molecular weight	17.031
Boiling point	- 33 ℃
Vapor pressure (20 ℃)	758 kPa
Density (1 atm)	0.86 kg/m^3 (Gas), 681.9 kg/m^3 (Liquid)
Water solubility (20℃)	531 g/l
Explosive limit	15-28%
Autoignition temperature	651 ℃
Minimum ignition energy	8 mJ

2.1.1 Storage properties of ammonia

The energy content (mass energy density) of liquefied ammonia is 18.6 MJ/kg, which is 0.44 times that of gasoline, and its volumetric energy density is also low, requiring a tank that is approximately 4.1 times larger than that of diesel fuel.[3] In the event of ammonia leakage, it rises quickly in dry air owing to its buoyancy; however, when used onboard, it may cause corrosion on the hull surface because of its fast reaction with moisture in the air. Moreover, ammonia reacts with SOx and NOx to produce secondary air pollutants such as ammonium sulfate and ammonium nitrate, respectively; therefore, appropriate safety devices and regulations for its usage should be in place to prevent leakage.

[Table 2-2] Storage properties of marine fuels

<table>
<tr><th>Fuels</th><th>Energy density (GJ/m³)</th><th>Storage pressure (bar)</th><th>Storage temperature(℃)</th><th>Relative fuel tank size (with consideration of insulation)*</th></tr>
<tr><td>LNG</td><td>25.0</td><td>1</td><td>-162</td><td>2.3</td></tr>
<tr><td>Methanol</td><td>15.8</td><td>1</td><td>20</td><td>2.3</td></tr>
<tr><td rowspan="2">LNG</td><td rowspan="2">25.0</td><td>1</td><td>-34</td><td rowspan="2">4.1</td></tr>
<tr><td>10</td><td>20</td></tr>
<tr><td>LH2</td><td>8.5</td><td>1</td><td>-253</td><td>7.6</td></tr>
</table>

*Fuel tank size is calculated by setting the storage tank size of marine gas oil (MGO) as 1

2.1.2 Ignition/combustion characteristics of ammonia

Ammonia is a flammable gas with a high lower explosive limit and narrow range of flammability limits. The autoignition temperature is relatively high at approximately 651 °C; therefore, it must be ignited using a pilot fuel when used in internal combustion engines. As in the case of other gas fuels, ammonia must be separated from ignition sources; however, the risk of fire is relatively low because of the narrow range of flammability limits and difficulty in ignition. The combustion characteristics of next-generation marine fuels including ammonia are outlined in Table 2-3. Contact of ammonia with strong oxidizing agents, such as chlorine and sodium hypochlorite bleach, may produce explosive mixtures. Furthermore, as the combination of ammonia with mercury also forms explosive compounds, mercury should not be used in instruments that may come in contact with ammonia.

The relatively low flame speed and narrow range of flammability limits may lead to the incomplete combustion of ammonia, resulting in ammonia slip in engines. To supplement the combustion characteristics of ammonia, a technology to improve its combustion characteristics by using other fuels as a pilot fuel is under development.

[Table 2-3] Combustion characteristics of next-generation marine fuels

Fuels	Minimum ignition energy (mJ)	Autoignition temperature (℃)	Octane number	Maximum flame speed (m/s)
Ammonia	8	650	111	0.07
Hydrogen	0.018	520	130	2.91
Methane	0.28	630	120	0.37
Methanol	0.14	385	106	0.43
Diesel oil	20	210	25	1.28

In charge compression ignition (CCI) engines, which are predominantly used in large ships, fuel is injected with a high compression ratio at temperatures above the autoignition temperature for combustion. For the application of ammonia to CCI engines, research has been conducted on the use of diesel oil or dimethyl ether (DME) as a pilot fuel to ignite ammonia. Combustion experiments on ammonia were conducted at various mixing ratios, which are outlined in Table 2-4 with reference to a previous study.[4] In general, as the ratio of ammonia increases, the ignition delay also increases owing to the high autoignition temperature and slow flame speed, resulting in limited engine power. Considering these drawbacks, a previous study proposed that the ammonia ratio required in the ammonia-diesel fuel should be 10 to 90% to achieve optimum fuel economy under constant engine power.[5] Research has been conducted on the use of various fossil fuels, such as diesel, DME, and kerosene, as the pilot fuel, and the CO_2 emissions vary depending on the type of pilot fuel and its proportion in fueling combinations.

[Table 2-4] Mixed combustion: ratio of ammonia and pilot fuels

Reference	Pilot fuel	Ammonia
Zacharakis-Jutz (2013)	DME	20, 40, 60% (weight%)
Reiter and Kong (2008)	Diesel	10-90% (mol%)
Tay et al. (2017)	Diesel and/or kerosene	10-90% (energy%)
Gross and Kong (2013)	Diesel	20, 40% (weight%)
Ryu et al. (2014)	DME	40, 60% (weight%)

2.1.3 Risks of ammonia - Toxicity and corrosion

- Toxicity

Ammonia is a colorless, toxic substance with a pungent odor at ambient temperatures and atmospheric pressure. It is lighter than air and tends to accumulate in high places such as ceilings. However, owing to its high affinity for water, when the discharged ammonia absorbs moisture from air, its density increases above that of air; consequently, it settles close to the ground surface by forming white clouds. Moreover, periodic exposure to the ammonia odor causes olfactory fatigue or adaptation, and the olfaction ability may be significantly diminished leading to an inability in detecting the smell even at a high concentration of 300 ppm.[6] The toxicity of ammonia with respect to the exposure level and time is presented in Table 2-5.

[Table 2-5] Effects of ammonia inhalation on humans based on the concentration

Concentration (ppm)	Symptoms
5	Characteristic, offensive odor is perceptible
6-20	Eye irritation and problems to the respiratory tract
40-200	Headache, nausea, reduced appetite, irritation to airways, nose, and throat
400	Throat irritation
700	Immediate eye injury
1,700	Cough, wheezing, and shortness of breath
2,500-4,500	Fatal
≥5,000	Fatalities due to rapid respiratory arrest

In most countries, the exposure guideline levels permitted in the workplace or daily living environments are established and managed. The permissible exposure limit is divided into short-term exposure limit (STEL) for 15 min of contact and time-weighted average concentration (TWA) based on 8 h of work. In the case of ammonia, STEL and TWA are 35 and approximately 25 ppm, respectively. Based on the acute exposure guideline levels (AEGL) for airborne chemicals defined by the U.S. Environmental Protection Agency, the toxicity of ammonia according to its concentration and period of exposure is as listed in Table 2-6.[7]

[Table 2-6] Acute exposure guideline levels based on concentration and period of ammonia exposure

	10 min	30 min	60 min	4 hour	8 hour
AEGL 1	30 ppm	30 ppm	30 ppm	30 ppm	30 ppm
AEGL 2	220 ppm	220 ppm	160 ppm	110 ppm	110 ppm
AEGL 3	2,700 ppm	1,600 ppm	1,100 ppm	550 ppm	390 ppm

· AEGL 1: The general population may experience irritation, etc., but the effects are transient and reversible upon cessation of exposure
· AEGL 2: The effects may be irreversible or lead to long-lasting adverse health effects
· AEGL 3: The general population may experience life-threatening health effects or death.

Because ammonia is highly soluble in water, it is absorbed through bodily fluids (sweat, tears, saliva) and can cause severe chemical burns. In the event of an ammonia leakage accident, special attention should be paid to the safety of the crew and emergency equipment in the ammonia handling space.

When ammonia is leaked, a water spray is used as an effective means of absorbing ammonia from the air. To prevent injury to people who came into contact with ammonia, emergency showers and washrooms must be installed in the ammonia handling zone, and ventilation devices in accommodation and work areas should be designed to prevent the inflow of ammonia.

Ammonia is not only toxic to humans, but also has an adverse impact when released in large quantities to the ecosystem. If ammonia is discharged into an aquatic ecosystem, it can destroy the ecosystem by causing eutrophication. Eutrophication refers to a phenomenon in which nutrients such as phosphorus and nitrogen become overly abundant in water, causing excessive algal growth, which reduces the amount of dissolved oxygen and kills living organisms in water. Therefore, the impact of ammonia on the ecosystem in the event of ammonia leakage onboard must be analyzed and appropriate regulations must be established and implemented.

The Korean Register (KR) published “Guidelines for Ships Using Ammonia as Fuels” in 2021,[8] and these guidelines are applicable to ships using ammonia as fuels according to the Rules for the Classification of Ships Using Low-flashpoint Fuels. Considering the main properties and risk factors of ammonia, the guidelines specify revised requirements as well as additional requirements for the Rules for the Classification of Ships Using Low-flashpoint Fuels.

- Corrosion

Ammonia is corrosive to some materials, such as copper, copper alloys, and zinc, and this should be considered when selecting these materials. Ammonia is known to cause stress corrosion cracking in carbon manganese steel or nickel steel. Consequently, fuel tanks, pressure vessels for manufacturing, and piping systems for fuel where carbon manganese steel is used must be manufactured from fine-grained steels with a minimum yield strength of ≤ 355 N/mm^2 and an actual yield strength of ≤ 440 N/mm^2. The ammonia storage temperature should be maintained as close as possible to the ammonia boiling point of -33 ℃ and should not exceed a temperature of -20 ℃ under any circumstances. Moreover, oxygen dissolved in liquid ammonia increases the risk of stress corrosion. Therefore, the level of dissolved oxygen must be maintained below 2.5 ppm (w/w) and air must be purged before injecting ammonia into the ammonia fuel supply system (FSS) or a tank.[9]

The risk of stress corrosion cracking can be significantly reduced by adding a small amount of water, not less than 0.1 wt%. Moreover, when ammonia is stored and transported at high pressure, the risk of stress corrosion cracking can be reduced by using a tank treated with post-weld stress relief. To prevent stress corrosion cracking, the use of steels with nickel content greater than 5% is generally prohibited. For materials such as rubber, plastic, vinyl, or aluminum alloys, only those approved by the KR should be used considering the conditions of use.

It is true that currently, each classification society has different regulations for using ammonia as a fuel. In the future, ammonia will be included in the International Code of Safety for Ships using Gases or other Low-flashpoint Fuels (IGF Code) determined by the IMO Carriage of Cargoes and Containers (CCC) Sub-Committee to establish regulations for uniform and consistent applications.

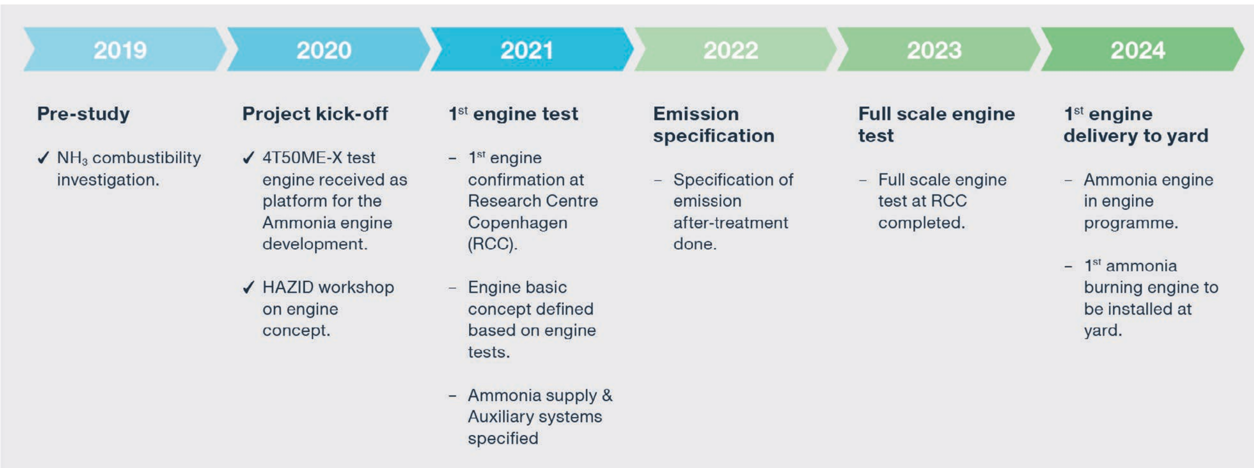
2.1.4 Ammonia exhaust gas

In the process of ammonia combustion, the slip phenomenon of unburned ammonia and NO_x and N2O emissions, which are combustion by-products, may occur; thus, an exhaust gas after-treatment system is necessary for treating these emissions.[10] NO_x emissions may be reduced using a selective catalytic reduction (SCR) system, which is an exhaust gas after-treatment technology. When applying the SCR system, ammonia is used as a reducing agent and converts NO_x into nitrogen and water. In ammonia-fueled ships, NO_x can be treated by injecting some of the ammonia into an SCR system

2.2 Overview of Ammonia-fueled Engine Development

2.2.1 MAN Energy Solutions

MAN Energy Solutions (MAN ES) is working on the development of a two-stroke ammonia dual-fuel engine and plans to complete the development by 2024. The two-stroke diesel engine is based on the compression ignition method and is the preferred type of main propulsion system for large ships. MAN ES explains that ammonia as a fuel has poor ignition and combustion characteristics; however, for marine engines, the low speed and large volume provide time for the completion of combustion and lowers heat losses; thus, the combustion characteristics of ammonia can be utilized as advantages in the design of the engine.[11]



|Fig. 2-1| MAN Energy Solutions - two-stroke ammonia engine development road map[11]

In the development of ammonia engines, MAN ES has started by developing the ME-LGIP engine, a two-stroke liquefied petroleum gas (LPG) dual-fuel engine. The operating conditions of LPG and ammonia engines are similar; however, differences in terms of the calorific values and corrosion characteristics between the two engines must be considered. According to the data published by MAN ES, ammonia is supplied to the engine at a pressure of 80 bar, and pressurized to 600-700 bar through the fuel injection valve for injection into the combustion chamber. Moreover, a pilot fuel is required for the ignition of ammonia owing to its poor combustion characteristics; therefore, marine diesel oil/heavy FO (HFO) are used as pilot fuels, which are also used in the conventional dual-fuel engine. Development is underway to achieve a 5% target ratio of pilot fuel in terms of energy[12]; moreover, for the implementation of actual zero-carbon fuels, biofuels or e-diesel should be utilized as pilot fuels.

2.2.2 Wärtsilä

Wärtsilä, a technology group for manufacturing engines and energy equipment, initiated combustion trials using ammonia in 2020 to perform optimization of combustion parameters. Wärtsilä aims to develop a complete ammonia fuel solution encompassing fuel supply and storage as well as engine development. The company is also working in collaboration with shipowners, shipbuilders, classification societies, and fuel suppliers to analyze the system and safety requirements, fuel composition, exhaust, emissions, and efficiency.[13]

Wärtsilä is developing ammonia storage and supply systems as part of ShipFC, an EU project to install ammonia fuel cells on vessels. The company has also gained experience with the use of ammonia from designing cargo process systems for ammonia carriers. Wärtsilä also has extensive experience in converting diesel engines to dual-fuel engines, as well as in the development of engines capable of burning volatile organic compounds from crude oil cargoes. The company predicts that further technology development in modular engines and in storage and supply systems will enable energy transition in the shipping industry from the current dependence on fossil fuels to zero-carbon fuels such as ammonia.

In 2002, Wärtsilä embarked on the Ammonia 2-4 Project for the development of marine engines running on ammonia fuel through a research initiative funded by the EU. Participants of the project include C-Job (naval architects), DNV (classification society), MSC (shipowner), and the National Research Council of Italy. The project is expected to demonstrate a four-stroke ammonia engine and develop a test engine with a vessel retrofit for the two-stroke engine. Wärtsilä has already completed the design of fuel blends of up to 70% ammonia and the company aims to complete the development of an engine running on pure ammonia by 2023.[14]

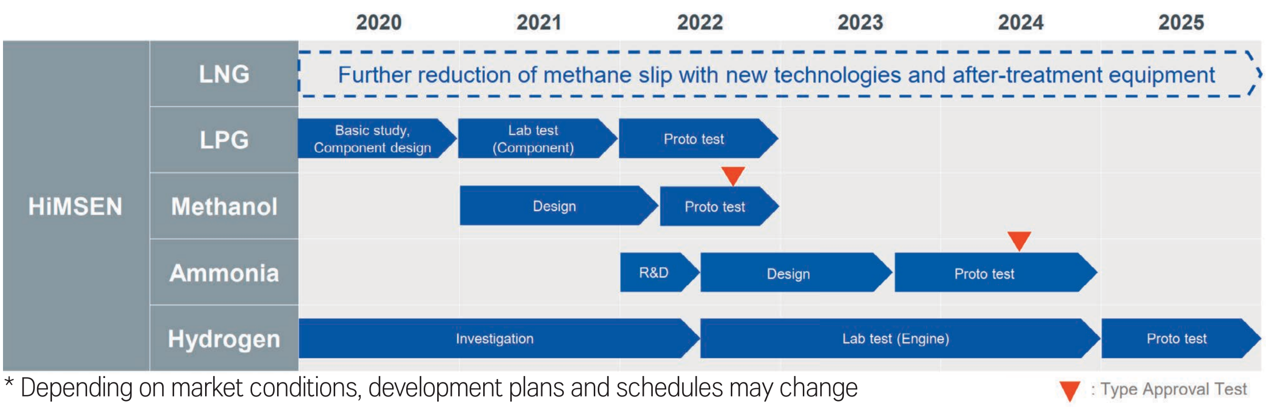
2.2.3 Hyundai Heavy Industries Group

Hyundai Heavy Industries (HHI) Group is engaged in the business of manufacturing two-stroke marine engines that were developed by MAN ES and Winterthur Gas & Diesel (WinGD) and their own four-stroke HiMSEN Engine, and is conducting R&D on clean engines with Korea Shipbuilding & Offshore Engineering, an intermediary holding company of HHI Group.

In 2022, HHI Engine and Machinery Division entered into a memorandum of understanding (MOU) with MAN ES for the development of two-stroke ammonia engines for ammonia carriers (aiming for the first release of a two-stroke ammonia engine in 2024).[15] In Posidonia 2022, an international shipping exhibition conducted in June 2022, the company signed an MOU with WinGD for joint research on ammonia engines (aiming for the release of two-stroke ammonia engines in 2025)[16], actively embarking on joint projects for the development of two-stroke ammonia engine designs for large ship propulsion, safety and fuel supply solutions, and exhaust gas after-treatment system.

Moreover, the HHI Group announced a development plan for its own four-stroke HiMSEN Engine powered by ammonia for an official launch in 2024.[17] Similar to the two-stroke ammonia engine, the ammonia-fueled HiMSEN Engine applies the dual-fuel concept that allows diesel mode operation, and research and technology developments are in progress to maximize GHG reduction, which is the ultimate goal of introducing ammonia as a marine fuel. In 2021, KR[18] and DNV[19] awarded the HHI Group an Approval in Principle for their conceptual design of low-flashpoint liquid fuel injection system, and the HHI Group continues to collaborate through government-funded projects for technology development on ammonia engines with related domestic and foreign institutions (KR, Korea Institute of Machinery and Materials, major universities in South Korea, etc.).

The HHI Group plans to build a lineup of sustainable carbon-free and low-carbon core fuels by launching methanol dual-fuel HiMSEN Engine in 2022 and ammonia dual-fuel HiMSEN Engine in 2024 in addition to the LNG dual-fuel HiMSEN Engine that was released in 2012.



|Fig. 2-2| Ammonia engine development schedule by the Hyundai Heavy Industries Group

2.2.4 STX Engine

STX Engine produces two-stroke low-speed engines and four-stroke medium-speed engines in technology partnerships with MAN ES. In 2019, they developed a pure gas engine (based on natural gas fuel) for ship propulsion, the first one in South Korea with its proprietary technology. The company announced that the engine obtained type approval from the KR.

STX Engine has also announced an ammonia-fueled internal combustion engine (four-stroke) project using a single-cylinder engine in response to the GHG reduction strategy of the South Korean government and tightened regulations of the IMO on GHG emissions.

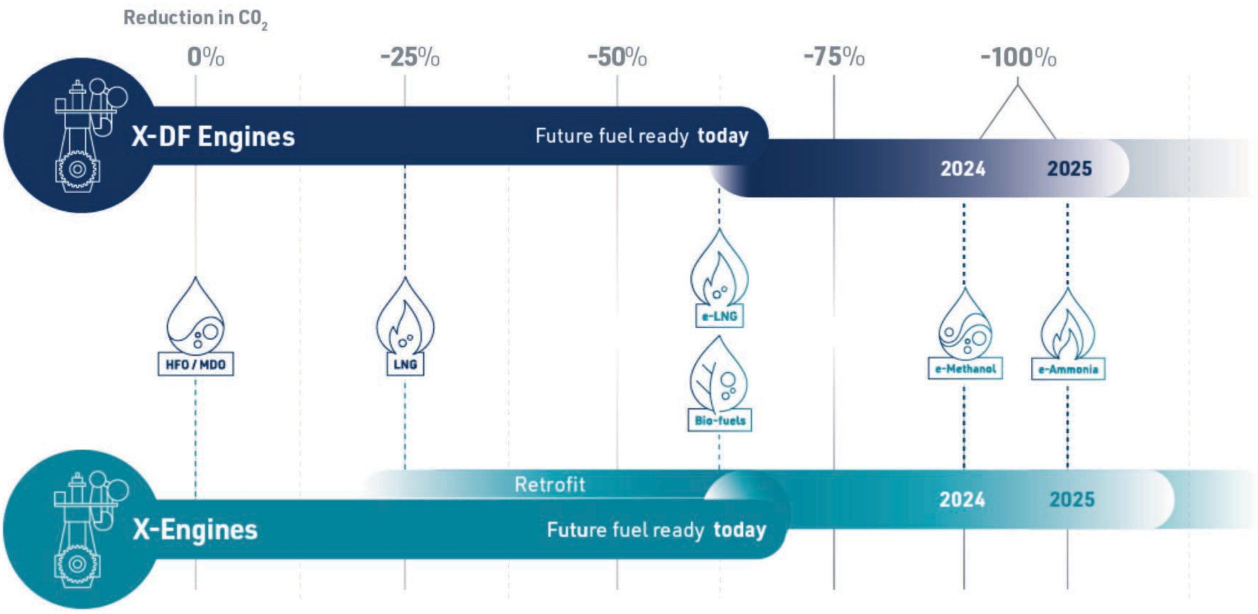
At the same time, STX Engine initiated a diesel-ammonia dual-fuel engine development project through a government funding initiative in 2021, and plans to conduct engine development and safety evaluation of ammonia fuel in collaboration with participating organizations. The ammonia engine under development by STX Engine is similar to the concept of the existing medium-speed, dual-fuel engines; however, in the case of engines operated using ammonia fuel, the difference in the dual-fuel combustion points between diesel and ammonia must be considered. STX Engine aims to minimize CO_2 emissions and verify reliability for durability of the developed engine by manufacturing the first prototype ammonia engine in 2023 and plans for onshore demonstration tests by 2024. Moreover, the company plans to develop a feedback control-based exhaust gas after-treatment system with its own technology, enabling simultaneous removal of NO_x generated in the process of burning ammonia and unburned ammonia gas, a toxic substance, for market release.

Furthermore, STX Engine plans to install an under-development ammonia engine on an ammonia dual-fuel propulsion system vessel in 2024 to conduct a sea trial and perform empirical evaluation for a safety system for ammonia fuel, thereby securing the safety of the newly developed ammonia engine.

2.2.5 Winterthur Gas & Diesel

WinGD, a Swiss engine developer, has announced the development of an engine running on methanol and ammonia by 2024 and 2025, respectively. The new multi-fuel solutions of WinGD will be based on their existing models of diesel-fueled X engine and dual-fuel X-DF engine. WinGD plans to apply zero-carbon or low-carbon fuels such as ammonia and methanol to all its core engine types, and is confident that their technology will provide ship operators with flexibility in their choices for reducing emissions. Furthermore, WinGD predicts that multi-fueled engines capable of operating on carbon-neutral fuels will account for 50% of the order book of the company by 2030.[20]

Furthermore, in 2002, WinGD signed an MOU with the HHI Group and announced that the companies will collaborate for delivering the first WinGD engine capable of running on ammonia by 2025. The project is set to include the development of relevant safety features, reduction of emissions, and fuel supply solutions for ammonia engines. WinGD announced that the project will give both WinGD and the HHI Group a substantial advantage in the development of ammonia-fueled marine engines, and lead the path for the next generation of two-stroke engine technology that is applicable to a wide range of cargo vessels in the coming decades.[21]



|Fig. 2-3| Winterthur Gas & Diesel - Timeframe for clean fuel engine development[20]

2.2.6 Japan Engine Corporation, IHI Power Systems

A consortium of Japanese companies including Nippon Yūsen Kabushiki Kaisha, Japan Engine Corporation, IHI Power Systems, and Nihon Shipyard have announced that, with the support of the New Energy and Industrial Technology Development Organization of Japan, they plan to develop the first domestically produced ammonia-fueled engine of Japan and install the engine on a tugboat by 2024, and by 2026, an ammonia engine will be used in an ammonia cargo vessel.[22] The consortium aims to develop an internationally competitive ammonia-fueled vessel and lead the development of safety guidelines, laws, and regulations related to ammonia-fueled ships.[23]

During the A-Tug project in which an ammonia engine will be installed on a tugboat, the companies aim to achieve an ammonia fuel mixed combustion rate ≥ 80%, and in the larger-scale project with an ammonia-fueled ammonia gas carrier, the target is to achieve a maximum ammonia fuel mixed combustion rate of 95% for the main engine of the ship, and an ammonia fuel mixed combustion rate of ≥ 80% for the auxiliary engine so as to reduce GHG emissions.

2.3 Ammonia Fuel Tank

Ammonia is liquefied at -33 °C at 1 atm, and LPG is liquefied at -42 °C at 1 atm. Therefore, ammonia can be stored in LPG tanks. As can be seen from the storage characteristics listed in Table 2-2, the energy density of ammonia is higher when compared to LH2, which is a zero-carbon fuel. Ammonia fuel exhibits significant advantages in terms of storage as it can be easily liquefied for storage when compared to LH2 and has a higher energy density. However, as ammonia has high toxicity and corrosiveness, leakage of ammonia must be prevented and appropriate materials must be selected for designing an ammonia fuel tank.

2.3.1 Design characteristics of an ammonia fuel tank

The International Code for the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk (IGC Code) classifies the types of ammonia tanks for use as A, B, C, and membrane types; however, in practice, types A and C are mainly used. In the type A tank, ammonia is stored after cooling it to the liquefied state under atmospheric pressure, whereas, in the type C tank, ammonia is stored by applying pressure to the vapor pressure at ambient temperatures. If a type C tank is used as a fuel tank to store ammonia, the energy required for pressurization can be saved, but a type A tank is more advantageous for the storage of ammonia in large quantities.

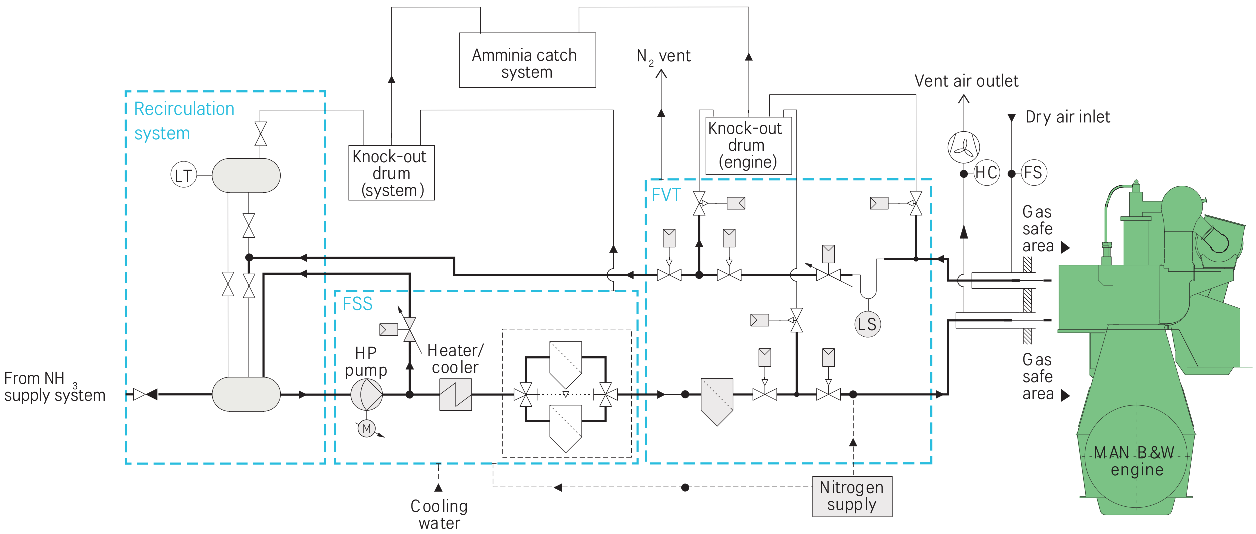
When designing an ammonia fuel tank, copper and copper alloys that are susceptible to corrosion should not be used, and the design tensile strength of the steel plate should not exceed the maximum allowable value. Ammonia storage tanks also require nondestructive testing and post-weld heat treatment to prevent leaks. A 100% nondestructive test is performed on the welded joint of the ammonia storage facility, and if the tank passes the nondestructive test, post-weld heat treatment should be applied on the welded joint.

2.3.2 Vessel designs with an ammonia fuel tank

Restrictions on determining the locations of tanks and fuel pipes are expected to be similar to the requirements for LPG fuel, and minimum distances from the side and bottom of the vessel should be set to prevent the risk of tank damage under collision and stranding scenarios. The ammonia tank should be located far from the engine room and other areas with high fire risk and should be protected from locations where crane operations occur or other areas with risk of mechanical damage. Moreover, storage tanks and equipment located on the open deck should be installed in a place with sufficient natural ventilation so that the discharged gas is not gathered to a specific area. The maximum allowable relief valve setting of the facility storing ammonia may exceed 1.0 MPa, and if the fuel tank connection is positioned on the open deck, risk assessment should be performed to check for possibilities of the collection of leaked ammonia or diffusion into nonhazardous area such as accommodation space or machinery space. If risk of ammonia diffusion is identified, the tank should be installed in an area that allows isolation of tank connection space and the exhaust ventilation outlets should be located in safe locations.[24],[25]

2.4 Ammonia Fuel Supply System (FSS) (MAN ES - Two-stroke Dual-fuel Engine)

2.4.1 Structure of ammonia FSS



|Fig. 2-4| ME-LGIA engine fuel supply system[26]

1. FSS

An FSS consists of a high-pressure pump, a heat exchanger, valves, filters, and control systems. In the FSS of the ammonia-fueled engine currently in development by MAN ES, a supply pressure of 80 bar is applied to ammonia using a pump. Through a heat exchanger, ammonia fuel is delivered to the engine at the required temperature range (~25-55 ℃).

2. Fuel valve train

A fuel valve train (FVT) is the interface between the engine and the auxiliary systems and consists of double block-and-bleed valve arrangements, a vent valve, a nitrogen supply valve, a pressure control valve, and various sensors. The purpose of FVT is to enable safe isolation of the engine from the fuel during shutdown due to abnormal events and maintenance activities, and to provide a nitrogen-purging functionality for effective discharge of residual fuel so as to ensure safety of the FSS.

3. Recirculation system

The recirculated ammonia will be separated to avoid two-phase conditions. The ammonia returned from the engine may be contaminated by other substances such as the oil in the engine; thus, it is not directly sent to the fuel tank but recirculated within the FSS. The ammonia gas separated from the recirculation system is discharged to the knock-out drum, and the ammonia gas that is stabilized in the knock-out drum flows into the ammonia catch system.

4. Nitrogen purge system and knock-out drum

Nitrogen purge system is needed to supply nitrogen for purging the engine after dual-fuel operation, for fuel discharge prior to maintenance and tightness testing after maintenance. The capacity of the nitrogen purge system must be sufficiently large to allow outflow of all remaining substances in the system at a pressure higher than the service tank pressure. The knock-out drum prevents ammonia from being released in a liquid state in the event of ammonia leakage or shutdown.

5. Ammonia catch system

Because ammonia is highly toxic and corrosive, ammonia released from the FSS must be captured. The property of ammonia with high absorption in water can be applied to the ammonia catch system. As for the absorption method, ammonia can be directly dissolved by spraying either water from a scrubber or exhaust gas into a water tank; alternatively, adsorption using activated carbon can also be used.

2.4.2 Operating principles of ammonia FSS

(1) When the engine is not running on the dual-fuel mode, the engine and FSS are depressurized through the FVT, and the engine room is completely isolated from the ammonia fuel supply and return systems. Before operating the engine on ammonia fuel, the systems are pressurized with nitrogen to verify the tightness of the system by checking for leakages in the system.

(2) During dual-fuel operation, the valves of the supply and return lines are open and valves of the vent line are closed. The ammonia fuel fed to the engine is supplied from the storage tank through FSS. To maintain the required fuel conditions in the engine, some of the ammonia fuel is continuously recirculated to the FSS through the recirculation system.

(3) When the dual-fuel operation stops, the high-pressure nitrogen pushes the ammonia from the engine to the recirculation system. During the dual-fuel mode operation, the double-walled ventilation system in the engine room detects any ammonia fuel leakage and directs the leaked ammonia away from the engine room to a separate ammonia catch system. When the purging operation is complete, the valves of the supply and return lines will be closed in the FVT, and once again, the engine room will be isolated from the supply and return system. After complete isolation, the valve in the vent line will be opened to depressurize the engine system.

In the event of shutdown due to ammonia leakage or an emergency, the ammonia in the ammonia FSS must be quickly discharged. Therefore, in its design, the capacity of the ammonia catch system should be based on the scenario in which the largest amount of ammonia must be captured.

2.5 Development of International Regulations

The IGC Code sets forth provisions for safe handling of ammonia on ships. The IGC Code prohibits cargo that is classified as toxic from being used as fuel; thus, review and revision of these clauses are required to use ammonia as fuel in ammonia carriers. Moreover, detailed requirements for ammonia fuel must be stated in the IGF Code, which presents international regulations on the use of low-flashpoint fuels. The KR presented the following as items for additional risk assessment in consideration of the properties of ammonia.[8]

- For use of ammonia as a marine fuel, risk assessment must be performed to identify possible hazards to the hull, ship equipment, and crew.
- In relation to gas leakage, risk assessment should be performed in the following areas to ensure an equivalent level of safety as that of LNG fuel in the event of gas leakage: tank connection area, fuel preparation room, bunkering area, area around the vent mast, space between double pipes, enclosed area of the gas valve unit, tank storage window area.

At the 105th session of the IMO Maritime Safety Committee held in April 2022, a review of the guidelines pertaining to ships using ammonia as an alternative fuel was proposed. As a result of the session, participants agreed that the guidelines on the safety of ammonia-fueled ships must be reviewed by 2023. In this regard, safety measures for ammonia-fueled ships were reviewed at the 8th CCC Sub-Committee conducted in September 2022, and discussions were held on Agenda item 13, which focuses on the development of guidelines for the safety of ships using ammonia as fuel. Before this, at the 7th CCC Sub-Committee, a request was made for the collection of information necessary for the safe use of ammonia as fuel, and in the 8th CCC Sub-Committee, information necessary for using ammonia onboard or in port areas was discussed, as well as key considerations for using ammonia as fuel. It was confirmed that the existing IGC Code and International Code for the Construction and Equipment of Ships carrying Dangerous Chemicals in Bulk can be used for fire prevention equipment and protection of human life, and the safety standards used in other industrial sectors such as refrigeration systems and ammonia production facilities can be used for gas leak detection. Issues for consideration included explosion prevention and leak detection related to ammonia vents, determining the opening height for ammonia vents and distance from accommodation spaces, major issues related to ship design, and installation of water tanks and scrubbers for controlling leaked gas in the event of ammonia leakage. Moreover, the meeting confirmed the necessity for the development of a model for accurate calculation of ammonia diffusion during venting and a method for the treatment of the exhaust gas containing ammonia. In the future, multifaceted approaches will be applied to resolve these issues, and it was also decided that the IGF Code for ammonia-fueled ships should be developed based on the results obtained.[27]

03

Ammonia production/bunkering

3.1 Definition of Clean Ammonia

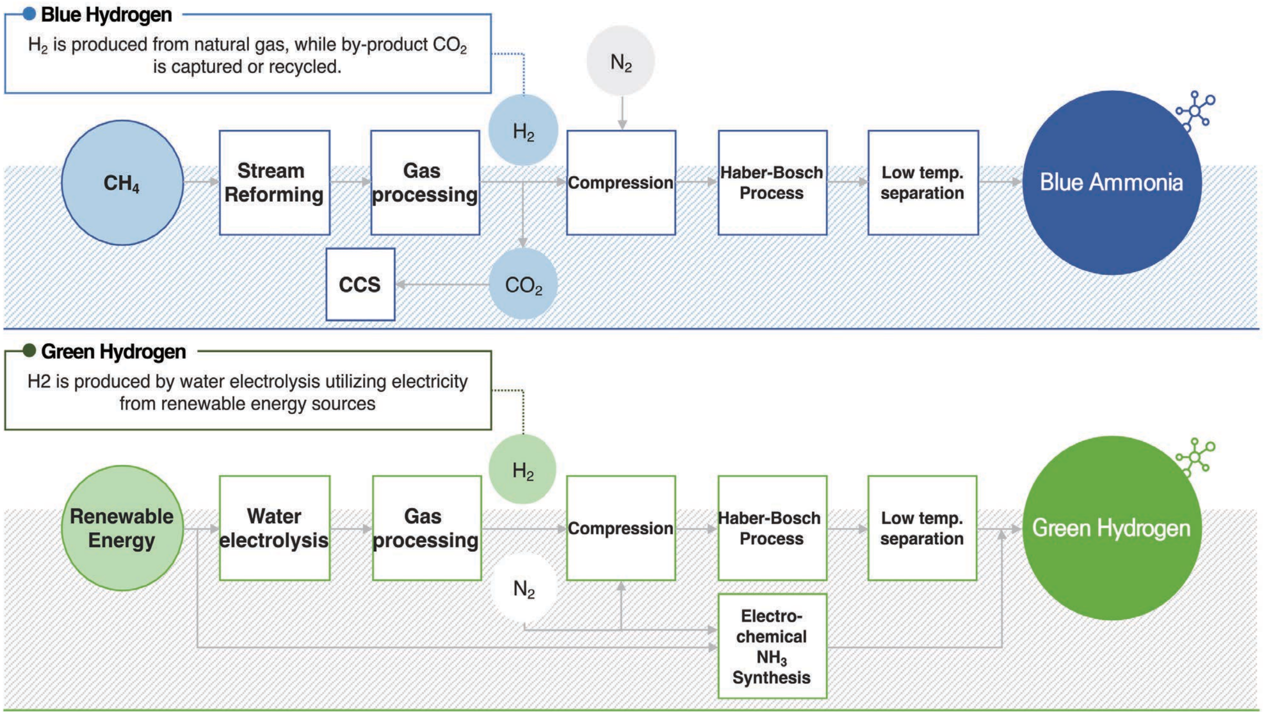
Clean ammonia comprises blue and green ammonia, which refer to ammonia that has been produced with minimal or no CO_2 emissions. Fig. 3-1 shows the process of producing blue and green ammonia. Ammonia is synthesized via the Haber-Bosch process, in which hydrogen and nitrogen are synthesized using iron-based catalytic reactions under conditions of high temperature (~500-600 ℃) and high pressure (≥150 bar). Thus, this process involves high energy costs. At this time, the ammonia is classified into blue and green ammonia depending on the type of hydrogen used.

Blue ammonia is synthesized using blue hydrogen produced via natural gas steam reforming, and the CO_2 produced with hydrogen in this method is processed through a carbon capture and storage (CCS) system or used in the utilization process. That is, blue ammonia is produced by supplying blue hydrogen to the Haber-Bosch process. The cost of this process is affected by variations in the cost of natural gas. Moreover, this process must be accompanied by the establishment of a carbon capture, utilization, and storage (CCUS) value chain. Gray ammonia produced using hydrogen from the natural gas reforming process without CCUS emits an average of 1.6 to 1.8 ton_{CO2}/ton_{NH3}, of which two-third is high-concentration CO_2 that is contained in the reformed gas, which is supplied to the CCUS value chain through the gas purification process. The remaining one-third is CO_2 emitted from the combustion fuel; therefore, securing an economic CCS value is challenging owing to its low concentration. Therefore, the economical CO_2 throughput in the blue ammonia production process is 1.07-1.2 ton_{CO2}/ton_{NH3}.

Green ammonia is produced by supplying green hydrogen generated through water electrolysis using renewable

energy to the Haber-Bosch process. By maximizing the use of renewable power in the process, the CO_2 concentration emitted during green ammonia production is minimized. Therefore, the production of green ammonia is significantly affected by the electricity cost generated from renewable energy sources such as solar and wind power and the water electrolysis production capacity. Currently, more than 85% of ongoing green hydrogen production projects worldwide are operated in connection with green ammonia production.

The following section presents a summary of the major clean ammonia production projects that are currently in progress.



|Fig. 3-1| Schematics for process of blue/green ammonia production[28]

3.2 Overview of Major Clean Ammonia Projects

3.2.1 Green ammonia projects

Since 2020, countries such as Australia, the Middle East, the U.S., and Canada with abundant resources of natural gas and renewable energy have actively promoted clean ammonia production projects involving the conversion of clean hydrogen into clean ammonia for export to countries such as Japan, South Korea, and Europe.

The production and trade of clean ammonia is expected to actively increase after 2025.

Saudi Arabia. The Helios Green Fuels project aims for an annual production of 1.2 MT of green ammonia from 4 GW of renewable energy facilities including solar, wind, and energy storage facilities in NEOM city, Saudi Arabia. Clean ammonia is produced using the water electrolysis technology of thyssenkrupp using electricity from renewable sources such as solar and wind power and the ammonia synthesis technology of Haldor Topsøe.

Australia. The Asian Renewable Energy Hub project plans for an annual power generation of up to 100 TWh of electricity using 26 GW of solar and wind power generation facilities in the Pilbara region of Western Australia, in addition to green hydrogen/ammonia production using renewable electricity and exports to other countries in 2027-2028. In October 2020, the first phase of the project to build 15 GW of solar and wind power generation facilities was approved by the Western Australian government. Another green ammonia project in the country, the Eyre Peninsula Gateway, aims to produce green hydrogen/ammonia in the Eyre Peninsula region. The project aims to produce 40,000 tons/year of green ammonia from a 75 MW water electrolysis facility with a 120 ton/day ammonia production facility in the first phase and 2,400 tons/day of green ammonia in the second phase of the project.

Denmark. The Dynamic Green Ammonia Plant project in Western Jutland is set to produce 5,000 tons/year of green ammonia by utilizing electricity generated from 12 MW (2 MW × 6 units) wind turbines and 50 MW photovoltaic facilities. The smart control system technology of Vestas that integrates electrolysis with solar and wind power and ammonia synthesis technology of Haldor Topsøe will be applied for this green ammonia project.

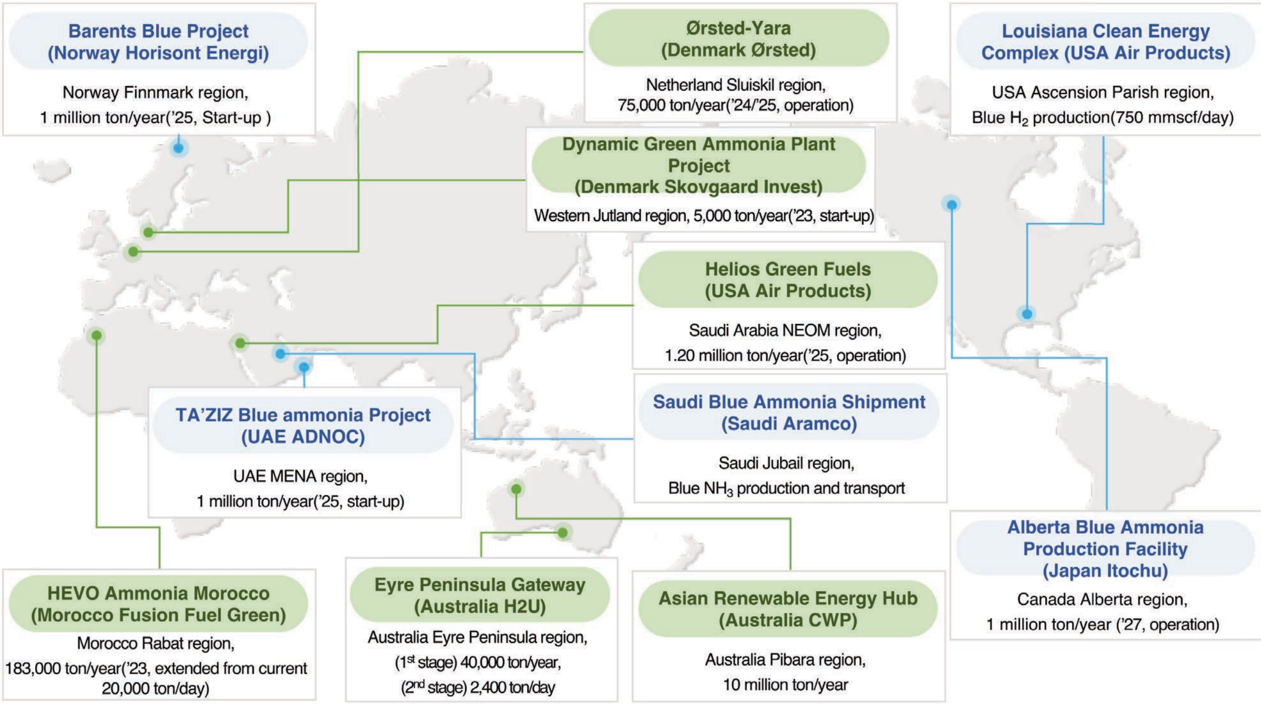
Morocco. The Fusion Fuel Green project aims to produce 183,000 tons/year of green ammonia in the Morocco Rabat region. Green hydrogen is produced through the HEVO-Solar system, and the produced green hydrogen is converted into green ammonia for export to Europe. Currently, a feasibility study and pilot operation of the project are underway, and green ammonia production targets of 20,000, 40,000, and 60,000 tons in 2023, 2024, and 2026, respectively, have been proposed.

Norway. A project is underway to produce 75,000 tons/year of green ammonia in Sluiskil, Norway. Ørsted is set to operate the world's second-largest 752 MW offshore wind farm off the coast of Zeeland, Norway. Based on the electricity generated from the offshore wind farm, green hydrogen will be produced through a 100 MW water electrolysis facility, and green ammonia will be produced at the Sluiskil plant of Yara, which will be used for the production of green fertilizer products.

Table 3-1 outlines the status of the current progress in green ammonia production projects with details of the project title, participating companies and country, country of origin (export country), destination country (import country), and project descriptions. Further, Fig. 3-1 shows an overview of major ammonia production and transportation projects.

|Table 3-1| Overview of major green ammonia production projects worldwide

Project title	Participating companies/agencies (governmental)	Country of origin (export)	Destination country (import)	Current status	Project description
Helios Green Fuels[29]	Air Products(U.S.), Acwa Power(Saudi Arabia), NEOM(Saudi Arabia)	Saudi Arabia	U.S. etc., (Worldwide)	Announced on July 7, 2020	· NEOM city, $5 billion hydrogen project · Green hydrogen production(650 tons/day), green ammonia production (1.2 MT/year) based on the technology proposed by Haldor Topsøe
Asian Renewable Energy Hub (AREH)[30]	CWP Renewables (Australia), Intercon-tinental Energy (Hong Kong), Vestas (Den-mark), Pathway Invest-ment (Australia)	Australia	Japan	Announced on October 20, 2020	· Western Australia East Pilbara, 22 billion Australian dollars · Renewable energy facilities with solar/wind power (26 GW) · Green hydrogen and green ammonia production in connection with renewable energy (23 GW)
Eyre Peninsula Gateway[31]	Hydrogen Utility (Australia), Government of South Australia(Australia)	Australia	Germany	Announced on June 11, 2020	· Eyre Peninsula · (Phase 1) Green ammonia production (40,000 tons/year) based on integration of water electrolysis (75 MW) and ammonia production facility (120 tons/day) · (Phase 2) Green ammonia production(2,400 tons/day)
Dynamic Green Ammonia Plant Project[32]	Skovgaard Invest (Denmark), Vestas (Denmark), Haldor Topsøoe (Denmark)	Denmark	To be con-firmed (TBC)	Announced on De-cember 9, 2020	· Denmark Western Jutland · Green ammonia production (5,000 tons/year) in connection with wind power (12 MW) and solar power (50 MW) · Scheduled for operation from 2023
HEVO Ammonia Morocco[33]	Fusion Fuel Green (Ireland), Consolidated Contractors Group (Greece), Vitol (Switzerland)	Morocco	Europe	Announced on July 13, 2021	· Morocco Rabat · Green ammonia production (183,000 tons/year) · Scheduled for full operation from 2026
Ørsted-Yara Project[34]	Ørsted (Denmark), Yara (Netherlands)	Norway	TBC	Announced on October 5, 2020	· Norway Sluiskil · Green ammonia production (75,000 tons/year) utilizing Borssele 1&2 wind farms (752 MW) and 100 MW water electrolysis facility · Scheduled for operation from 2024/2025

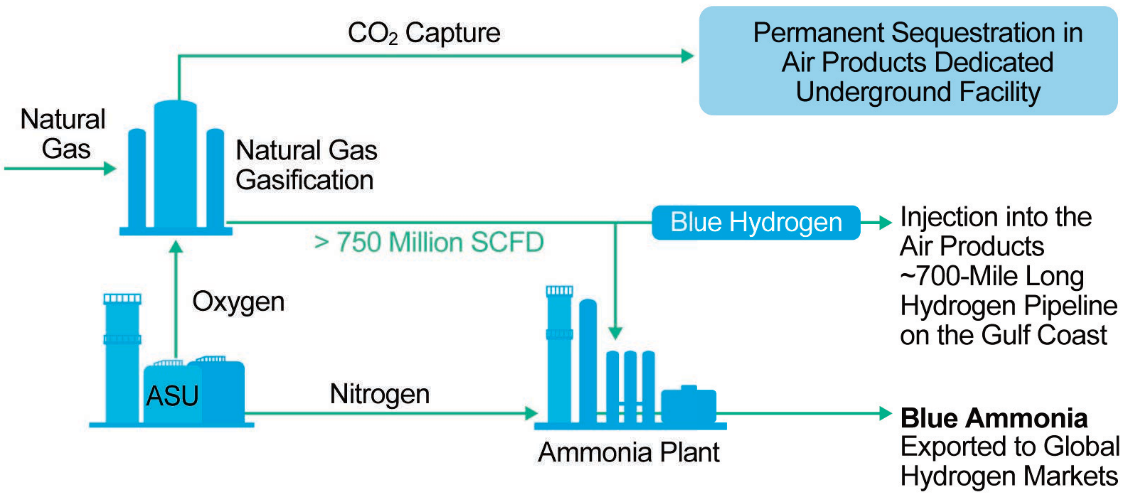


|Fig. 3-2| Overview of major ammonia production and transport projects worldwide

3.2.2 Blue ammonia projects

Saudi Arabia: Saudi Aramco exported 40 tons of blue ammonia to Japan for the first time in September 2020. Saudi Aramco and the Institute of Energy Economics Japan (IEEJ) signed an MOU, and Saudi Arabia Basic Industries Corporation (SABIC) joined the partnership.

U.S.: A project for the daily production of 750 million standard cubic feet of blue hydrogen in a natural gas gasification facility is underway in Ascension Parish, Louisiana. Blue ammonia will be produced using the technology proposed by Haldor Topsøe. Ninety-five percent (5 MT/year) of CO_2 generated from the production facilities will be captured and stored through CCS facilities. The figure below shows representative blue ammonia production projects.



|Fig. 3-3| [Fig. 3-3] U.S. Air Products blue hydrogen and ammonia production project[35]

Norway: The Barents Blue project plans for blue ammonia production of 1 MT/year in Finnmark, Norway. The project is scheduled to start in 2025 with production of blue ammonia using natural gas supplied from the Melkøya LNG plant, with CO_2 capture capacity of more than 99% using potassium carbonate and CO_2 storage capacity of 2 MT/year.

Canada: The Japanese firm Itochu and Malaysian national oil company Petronas are planning a joint project for blue ammonia production of 1 MT/year in scale in Alberta, Canada. A feasibility study was conducted for a facility to capture CO_2 emitted from the ammonia production process, and construction is planned to begin in 2023 with blue ammonia production from 2027. The blue ammonia produced from the facility will be shipped from western Canada to Japan, and will be used in power companies and steel/ironmaking and chemical industries in Japan.

UAE: In the TA'ZIZ Blue Ammonia Project, GS Energy of South Korea and the Abu Dhabi National Oil Company (ADNOC) of UAE have planned for the joint production of blue ammonia. The two companies signed an MOU in November 2021, planning to ship 200,000 tons of blue ammonia annually to South Korea for power generation after 2025, the year when the blue ammonia production plant is scheduled to start operations. The ammonia production plant in Ruwais, UAE, is expected to produce 1 MT/year of blue ammonia, and ADNOC has been running the Al Reyadah CCS project since 2016 with an annual capacity of capturing and storing 800,000 tons of CO_2 for the first time in the Middle East.

Table 3-2 presents a summary of the status of current progress for blue ammonia production projects including project title, participating companies and countries, country of origin (export), destination country (import), and a brief description of each project.

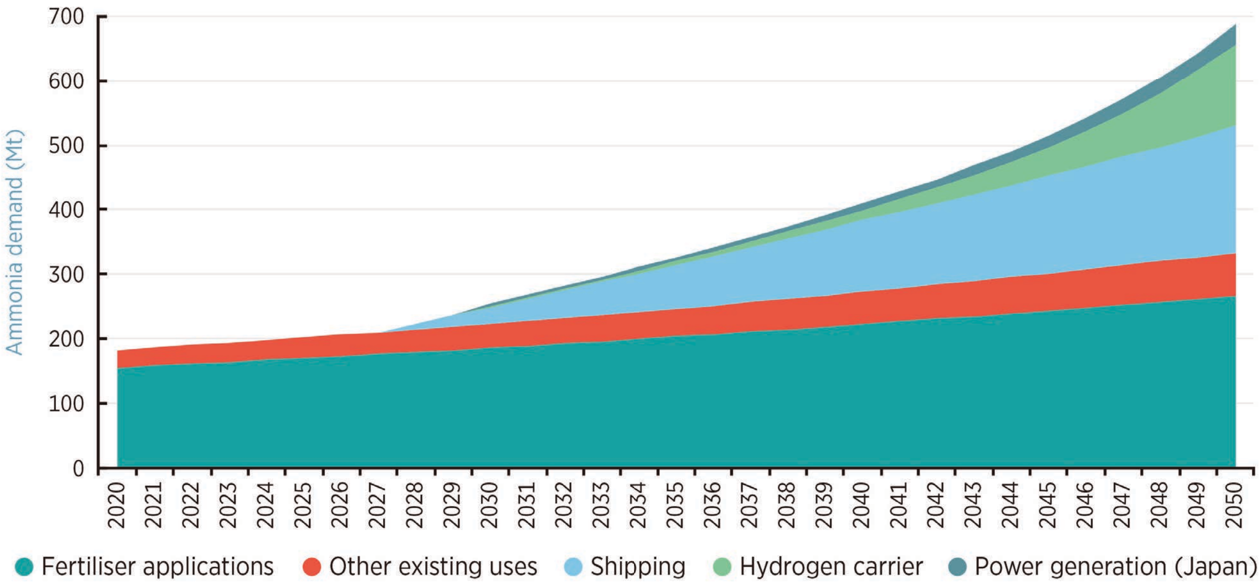
|Table 3-2| Overview of major blue ammonia production projects

Project title	Participating companies/agencies (governmental)	Country of origin (export)	Destination country (import)	Current status	Project description
Saudi Blue Ammonia Shipment[36]	Saudi Aramco (Saudi Arabia), IEEJ (Japan), SABIC (Saudi Arabia)	Saudi Arabia	Japan	First launched on September 27, 2020 (40 t NH_3)	· l Jubail, natural gas reforming + CCS blue hydrogen production · Blue ammonia production and transport · Ammonia 50 kW micro gas turbine, 2 MW gas turbine, dual-fuel boiler
Louisiana Clean Energy Complex[37]	Air Products (U.S.)	U.S.	TBC	Announced on October 14, 2021	· Ascension Parish, Louisiana State, $4.5 billion project · blue hydrogen production (750 million standard cubic feet /day) and CO_2 capture and storage(5M tons/year) · Scheduled for full operation in 2026
Barents Blue Project[38]	Horisont Energi (Norway), Equinor (Norway), Vår Energi (Norway)	Norway	TBC	Announced on September 9, 2021	· Norway Finnmark · blue hydrogen production (1M tons/year) and CO_2 capture and storage (2M tons/year) · Scheduled for operation in 2025
Alberta Blue Ammonia Production Facility[39]	Itochu (Japan), Petronas Energy (Malaysia)	Canada	Japan	Announced on August 3, 2021	· Canada Alberta, $1.3 billion project · blue ammonia production (1M tons/year) · Construction will start in 2023, Scheduled for operation in 2027
TA'ZIZ Blue ammonia Project[40]	ADNOC (UAE), GS Energy (ROK), Mitsui (Japan)	UAE	ROK, Japan	Announced on November 16, 2021	· UAE Ruwais · Aiming for blue ammonia production in 2025 (1M tons/year) · GS Energy and Mitsubishi: import of 200,000 tons per annum

3.2.3 Forecasting clean ammonia production

The estimated clean ammonia demand up to 2050 based on the scenario of limiting global warming to 1.5 ℃ is shown in Fig. 3-4. Currently, approximately 25-30 MT of ammonia are transported annually via ships, pipelines, and trains. From the figure, we can observe that, by 2050, the ammonia transport infrastructure must increase by a factor of 10-15 to accommodate 354 MT of additional ammonia that will be shipped around the world, requiring tens of billions of USD in annual investment in the infrastructure for storage and transport of ammonia.[41] Moreover, by 2050, approximately 735 additional ammonia storage tanks for 50 kt of ammonia will be required to account for one week of ammonia storage, which translates to a requirement for an investment of 20 billion USD.[42]

The Haber-Bosch process used for synthesis of ammonia requires high energy costs due to its operating conditions at high temperatures and high pressures. To reduce energy costs, active research has been underway for modifications to the Haber-Bosch process to allow efficient operation at lower temperatures and pressures or for energy supply based on electricity from renewable energy sources or nuclear power. Currently, most ammonia synthesis processes use hydrogen obtained from steam reforming; therefore, production of blue ammonia has problems related to the interconnection with the CCS project and natural gas cost. Meanwhile, green ammonia, which is obtained from hydrogen produced from renewables and nuclear power has gained increasing attention; however, the production scale may be restricted by the limited capacity of water electrolysis. In the future, largescale production and supply of clean ammonia is expected to practically be implemented only when these challenges have been overcome through technology development.



|Fig. 3-4| Forecast of clean ammonia demand up to 2050 for limiting global warming to 1.5 ℃[41]

3.3 Overview of the Clean Ammonia Market and Price

Table 3-3 lists a comparison of the prices for blue ammonia, green ammonia, hybrid gray ammonia, very-low sulfur fuel oil (VLSFO), and LNG. Assuming that ammonia takes the share of 30% of marine fuel by 2050, ammonia production of 150 MT/year is required. A total of 400 GW of renewable electricity is required to produce 150 MT of green ammonia. In the table below, the price estimation is represented based on the prices of blue and green ammonia, VLSFO, and LNG per energy content. The price of VLSFO is volatile, but it can be seen that the price per energy content in 2025 ranges from 12.5 to 15 USD/GJ. According to the estimate of LNG price from the

Annual Energy Outlook published by the U.S. Energy Information Administration (EIA) in March 2022, the price is expected to be in the range of 3.43-4.47 USD/GJ in 2030 and will increase to 6-7.26 USD/GJ in 2050. Maersk presents an LNG price estimate of 8.3 USD/GJ in 2030 and 8.8 USD/GJ in 2050. In the same report, the price of gray ammonia per energy content was maintained at an average value of 13.3 USD/GJ based on the period from 2018 to 2020.

The price of blue ammonia per energy content is expected to be in the range of 18.8-26.3 USD/GJ in 2030 owing to the increase in the cost of CCS and will decrease to the range of 13.4-22.0 USD/GJ in 2050. The price can be affected by variations in the natural gas cost and CCS cost.

The price of green ammonia per energy content is highly dependent on the price of electricity from renewable energy sources, ranging from 40.0-72.0 USD/GJ in 2020, but is expected to decrease to the range of 21.3-49.0 USD/GJ in 2030 and 14.8-31.0 USD/GJ in 2050. The comparison of blue and green ammonia prices per ton listed in Table 3-3 was based on the consideration of natural gas cost, CO_2 penalty, CCS cost, and electricity cost. The average price of green ammonia is expected to be in the range of 650-850 USD/ton in 2025, and will decrease to 400-600 USD/ton in 2030. LNG and VLSFO prices are based on their prices in 2020 and may be volatile depending on the international political landscape. The market prices of VLSFO, LNG, and blue and green ammonia were obtained by referring to data from previous research.

|Table 3-3| Price comparisons for blue ammonia, green ammonia, liquefied natural gas, and very-low sulfur fuel oil[43]

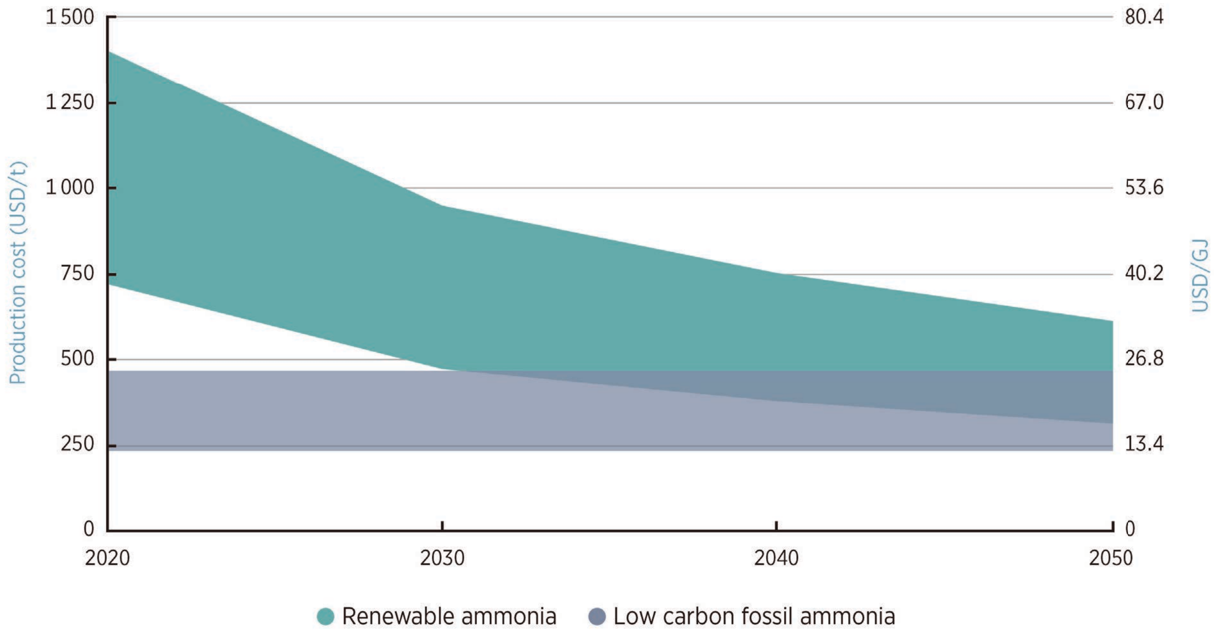
	2030		2050	
	Cost (USD/ton)	Cost (USD/GJ (LHV))	Cost (USD/ton)	Cost (USD/GJ (LHV))
VLSFO (<0.5%S)	500 - 600	12.5 - 15	500-600	12.5 - 15.0
LNG		3.43 - 8.2*		6.0 - 8.8**
Blue ammonia	350 - 400	18.8 - 26.3	350-400	13.4 - 22.0
Green ammonia	400 - 850	21.3 - 49.0	275-450	14.8 - 31.0

Note) 1 MMBtu = 1.05 GJ (LHV)

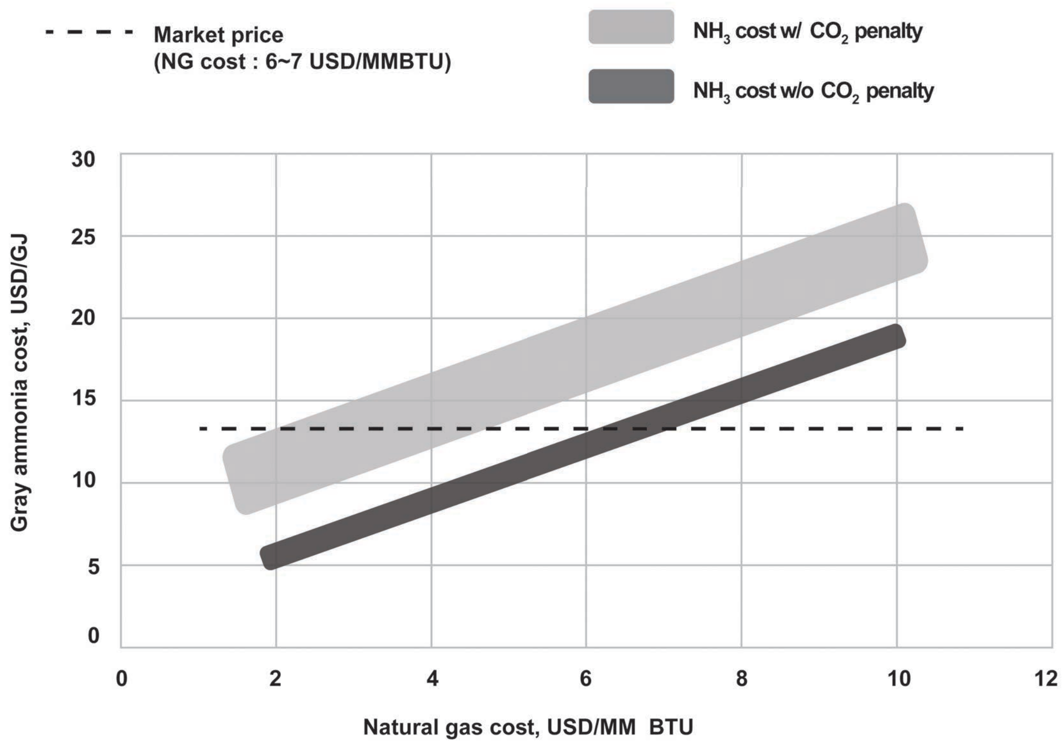
* EIA, Annual Energy Outlook, 2022, Maersk, Fuel Option Scenario, 2021

** EIA, Annual Energy Outlook, 2022, US natural gas price, Maersk, Fuel Option Scenario, 2021

Fig. 3-5 shows the result of forecasting the changes in the price of green ammonia and blue ammonia until 2050. Until 2030, the price of green ammonia is unlikely to be more competitive than that of blue ammonia; however, after 2030, the price of green and blue ammonia will become comparable. The prospect of market growth and mass distribution of green ammonia are key parameters for determining the reduction of market price.

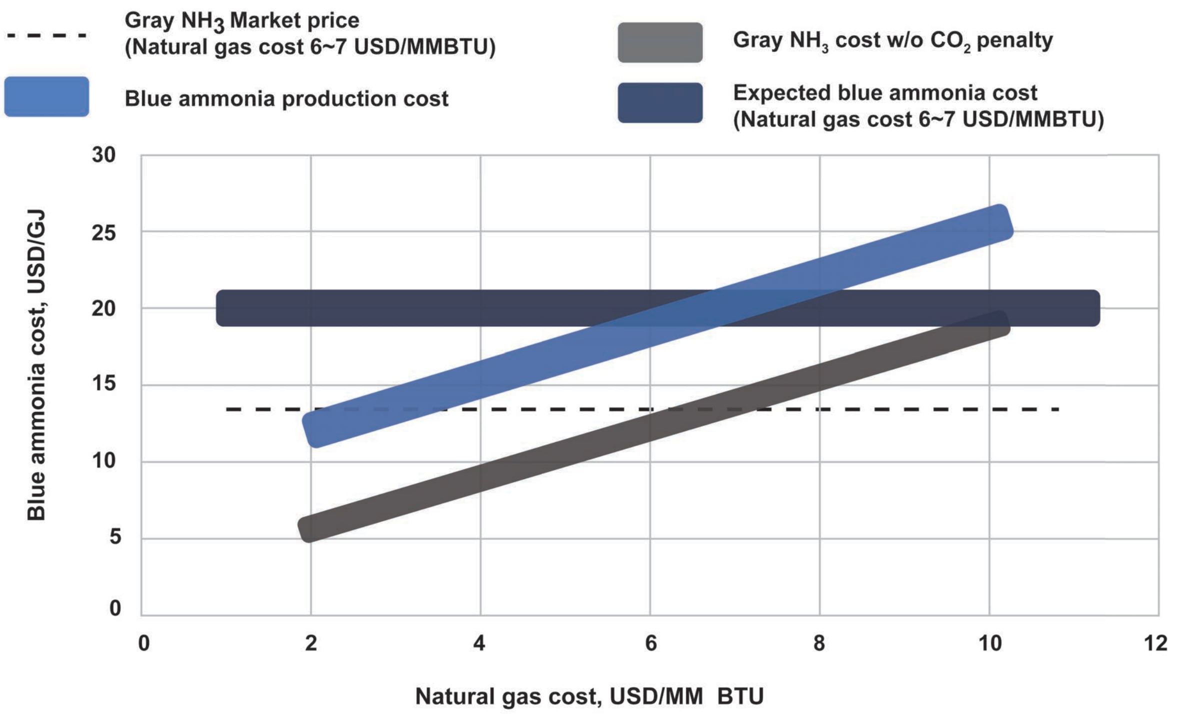


|Fig. 3-5| Projection of price changes in the future renewable ammonia market[41]



|Fig. 3-6| Changes in gray ammonia production cost according to natural gas cost and CO_2 penalty[43]

Fig. 3-6 shows the average market price of gray ammonia for the period from 2016 to 2020 (average natural gas cost 6-7 USD MMBtu) and gray ammonia price according to CO_2 penalty. Costs involved in gray ammonia production include fixed operating costs, cost of energy, and cost of CO_2 emission penalty. First, the future CO_2 penalty was assumed to be in the range of 25-75 USD/ton$_{CO2}$. As the energy cost accounts for 75-85% of the total cost, the cost of gray ammonia production is highly dependent on natural gas cost. The energy cost for gray ammonia production increases from 3.72 to 10.64 USD/GJ (70 to 200 USD/ton$_{NH3}$) when natural gas cost increases from 2.5 to 7.0 USD/MMBtu.

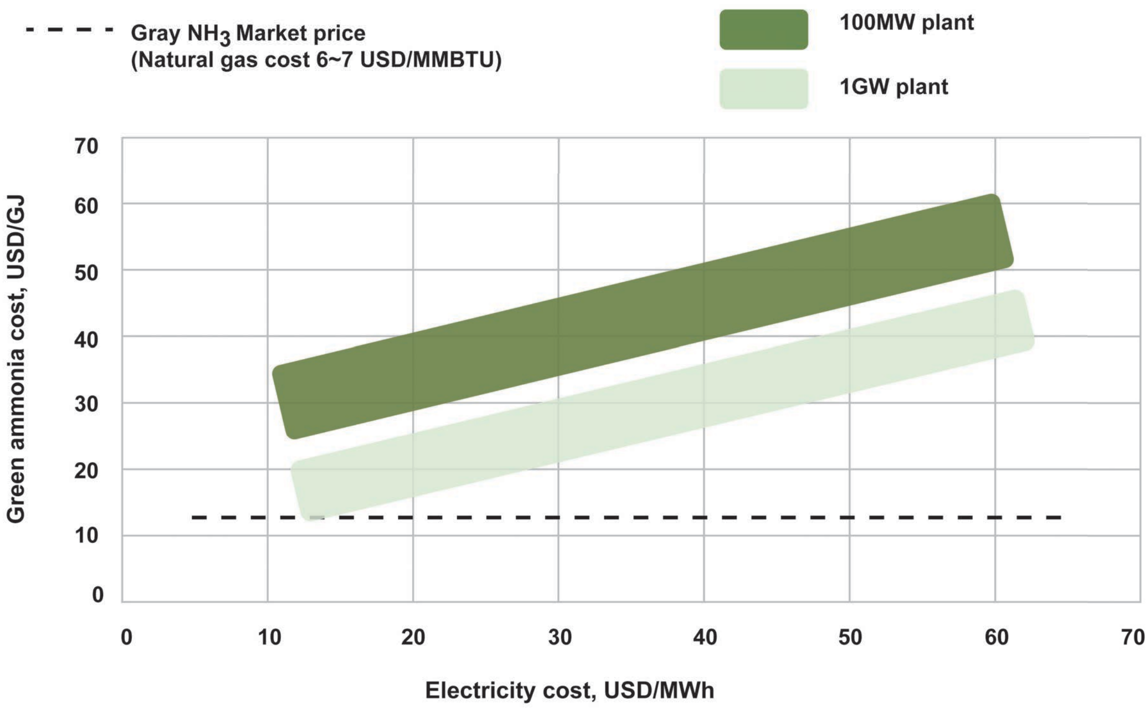


|Fig. 3-7| Changes in blue ammonia production cost according to natural gas cost and CO_2 penalty[43]

Fig. 3-7 shows the cost of blue ammonia production per energy content with average market price of ammonia for the period of 2016-2020 and gray ammonia cost without CO_2 penalty. The costs to be considered for blue ammonia production include the cost of gray ammonia production without CO_2 penalty, cost of CO_2 capture, and cost of CO_2 liquefaction, storage, and transport.

CO_2 in the feed gas supplied during blue ammonia production has a high concentration and can be easily recovered, while CO_2 generated from fuel use has a low concentration and requires high recovery costs. CO_2 generated from the natural gas reforming reaction is assumed to be 2 ton$_{CO2}$/ton$_{NH3}$, and the total CCS cost including costs of CO_2 capture, liquefaction, transportation, and storage is 100-150 USD/ton$_{NH3}$. Therefore, the estimated price of blue ammonia production per energy content is 18.6-21.3 USD/GJ (350-400 USD/ton$_{NH3}$), assuming an average natural gas cost of 6-7 USD/MMBtu, which is indicated in a dark-blue color in Fig. 3-6.

The unit cost of blue ammonia production, which increases along with the increase in natural gas cost, is represented in light-blue color. When the natural gas cost increases in the range of 2-10 USD/MMBtu, the price of blue ammonia increases to 10.0-26.3 USD/GJ. The unit price of blue ammonia production will vary depending on the cost of natural gas and CCS costs, and the range of price variation can be considerable depending on the situations of short- or long-term CO_2 storage. In particular, the blue ammonia production cost will be significantly affected by the CO_2 penalty that will be applied in the future.

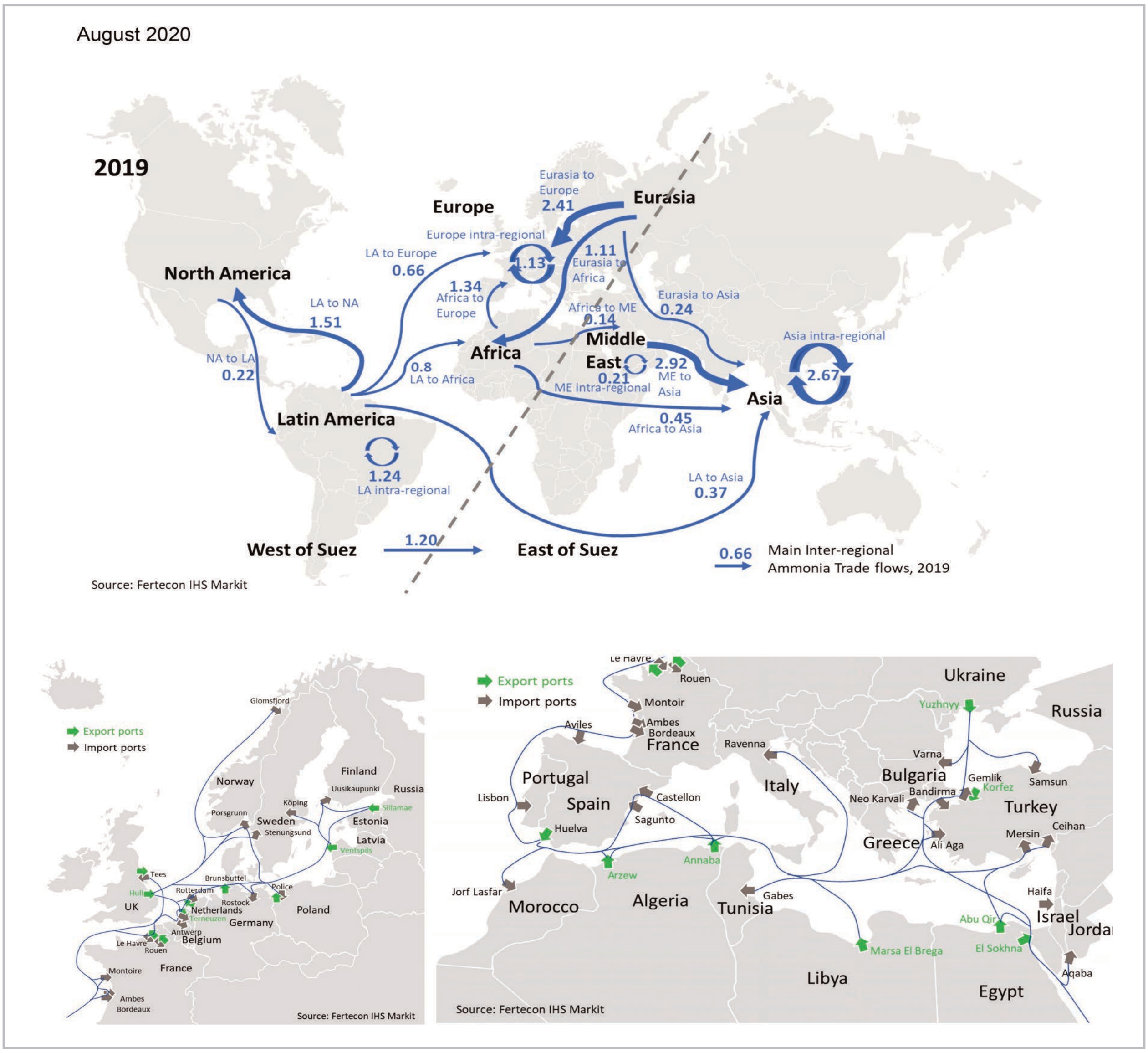


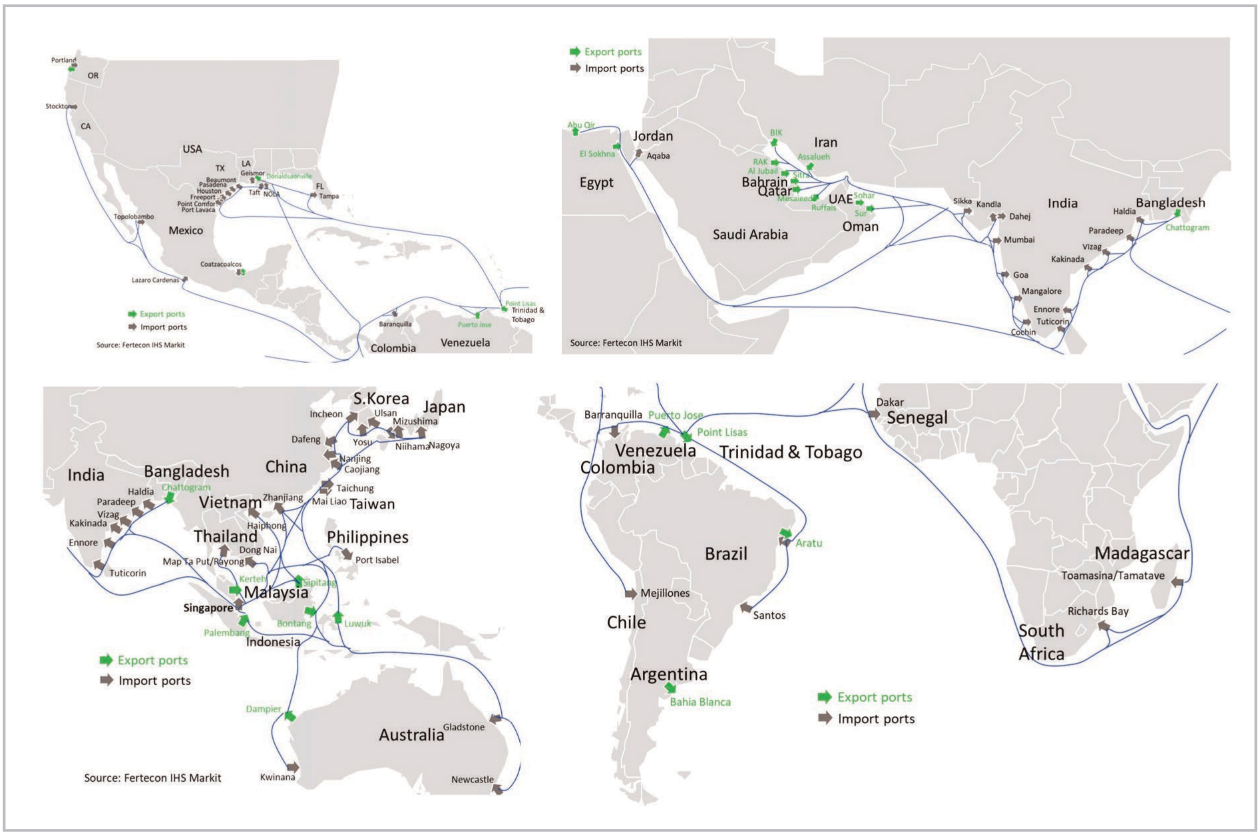
|Fig. 3-8| Changes in green ammonia production cost according to electricity cost and scale of production[37]

Fig. 3-8 shows the cost of green ammonia production per energy content at 1 GW and 100 MW plants based on the average market price of ammonia for the period 2016-2020. The costs to be considered for green ammonia production include: cost of capital investment, fixed operating costs, and cost of energy. For fixed operating costs, staff, overhead, maintenance, insurance, and storage costs are included. The process of green ammonia production includes water electrolysis, electrically driven air separation device, traditional Haber-Bosch synthesis at high-temperature and high-pressure conditions. The cost of green ammonia production including energy cost will range from 34.57 to 45.21 USD/GJ (650 to 850 USD/ton_{NH3}) in 2025, and decrease to the range of 21.28-31.91 USD/GJ (400 to 600 USD/ton_{NH3}) in the 2030s, and further decrease to 14.63-23.94 USD/GJ (275 to 450 USD/ton_{NH3}) in the 2040s. Fig. 3-8 shows that the unit cost of green ammonia production is significantly affected by the electricity cost, and accordingly, the green ammonia price will decrease as the cost of electricity produced from renewables or nuclear power decreases. Moreover, the unit cost of green ammonia production can be further reduced when applying water electrolysis technology from the scale of 100 MW to 1 GW because of the expansion of the production process. Therefore, the unit cost of green ammonia production can be expected to decrease through a decrease in electricity costs required for water electrolysis owing to a greater application of renewable sources such as wind, solar, and nuclear powers, an increase in the capacity of water electrolysis plants, and technological developments in ammonia synthesis.

3.4 Ammonia Logistics and Bunkering

Fig. 3-9 shows the distribution of gray ammonia terminals, with 38 export and 88 import terminals, 6 of which are for both import and export.[51] South Korea has terminals with storage facilities of 15,000 tons in Incheon,





Global distribution of ports for ammonia import/export and trade flows[43]

50,000 tons in Yeosu, and 93,000 tons in Ulsan. In the current distribution patterns, terminals are primarily located around areas with an abundance of the natural gas reserves for ease of producing and export of ammonia, and the ammonia is transported to places with demand of chemical fertilizers and raw materials for sale. Therefore, ports for import and export as well as infrastructure have already been built around the world, and with the increase in projects involving ammonia production and export, the number of ammonia bunkering ports is expected to increase.

By utilizing the already established grid of ammonia terminals and storage facilities, a bunkering network can be established promptly with cost efficiency by converting small gas tanker vessels to bunker barges. The existing storage facilities can be utilized as base stations, and the bunker barges can approach the vessels requiring bunkering to perform bunkering operation. Currently, with active planning and implementation of a number of largescale clean ammonia production projects, various logistics-related projects are underway in preparation for a high volume of trade in clean ammonia.

Netherlands: The Transhydrogen Alliance is undertaking the construction of green ammonia terminals for green hydrogen imports at the Port of Rotterdam in the Netherlands (March 2021). The project targets the import of up to 2.5 MT of green ammonia per annum via the terminal in the Port of Rotterdam, which is converted from up to 500,000 tons of green hydrogen produced from the Pecém Complex in the State of Ceará, Brazil, and committed to an investment of $2 billion (November 2021).

Singapore: Maersk and Keppel Offshore & Marine entered into an MOU for a joint feasibility study for establishing a green ammonia bunkering hub at the Port of Singapore (March 2021). A feasibility study covering the development of a cost-effective green ammonia supply chain, design of ammonia bunkering vessel, and development of related green ammonia supply chain infrastructure is underway.

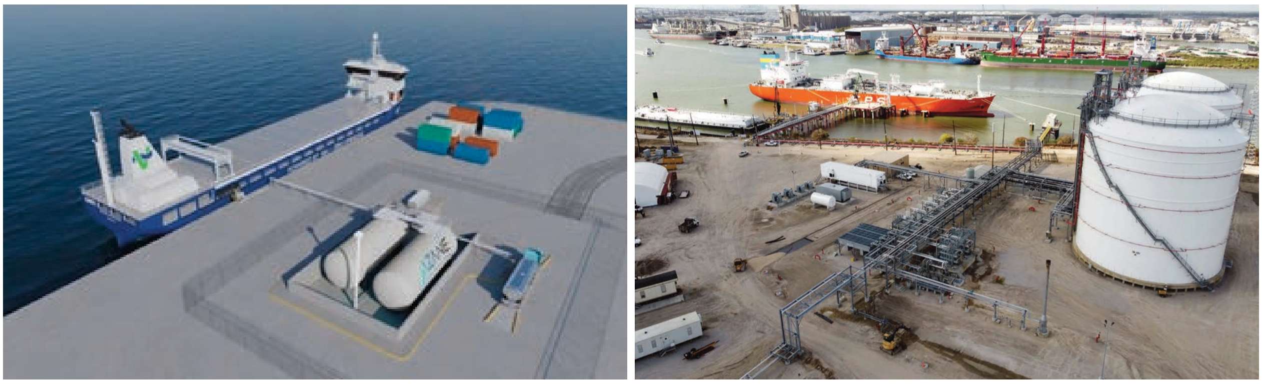
Australia: RWE Supply & Trading plans to use the LNG terminal planned in Brunsbüttel, located at the coast of the North Sea, as the green ammonia export terminal by importing green hydrogen produced in Australia to Germany.

Norway: Azane Fuel Solutions is undertaking construction of the first green ammonia bunkering terminals and network (September 2021). Construction of port- or barge-based bunkering infrastructure is planned and the plans for development of an optimized bunkering solution that supplies refrigerated or pressurized clean ammonia from ships, trucks, barges, etc. as fuel to ships are included in the project.

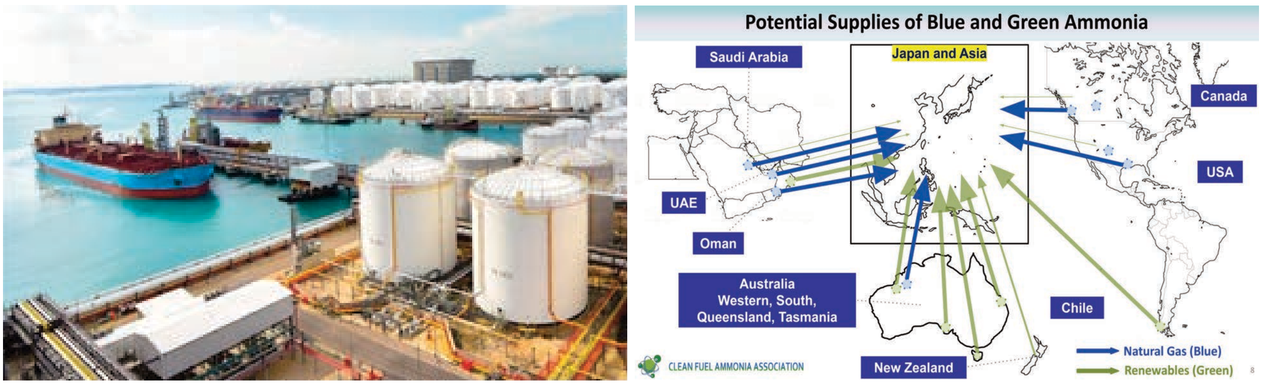
U.S.: Vopak Moda Houston completed the construction of a terminal for storage and distribution of clean ammonia at the Port of Houston, U.S. (December 2021). It is an ammonia terminal for seaborne transportation at the Port of Houston designed to handle the berthing of very large gas carriers as well as smaller vessels and

barges. Clean ammonia is supplied to the Port of Houston, which is the second-largest petrochemical complex in the world and the largest in the nation, through pipelines, and transported through railroad infrastructure.

Japan: To increase clean ammonia consumption in Japan to 3 MT/year by 2030, joint ventures have been signed (March 2021) to build an ammonia supply hub and develop ammonia-fueled ships. Itochu is in charge of building an ammonia supply hub in Japan and developing bunkering vessels, Ube Industries is responsible for the development of onshore facilities for marine fuel supply, and Uyeno Transtech is responsible for developing ammonia bunkering vessels and formulation of their safety standards. Fig. 3-10 shows the ammonia terminal plans for Norway and the U.S., and Fig. 3-11 illustrates the terminals in Singapore and Japan. Table 3-4 lists an overview of the current status of major ammonia bunkering and logistics projects.



|Fig. 3-10| (Left) Conceptual schematic of ammonia bunkering terminal at Norway[44]; (Right) Ammonia terminal of Vopak Moda Houston, U.S.[45]



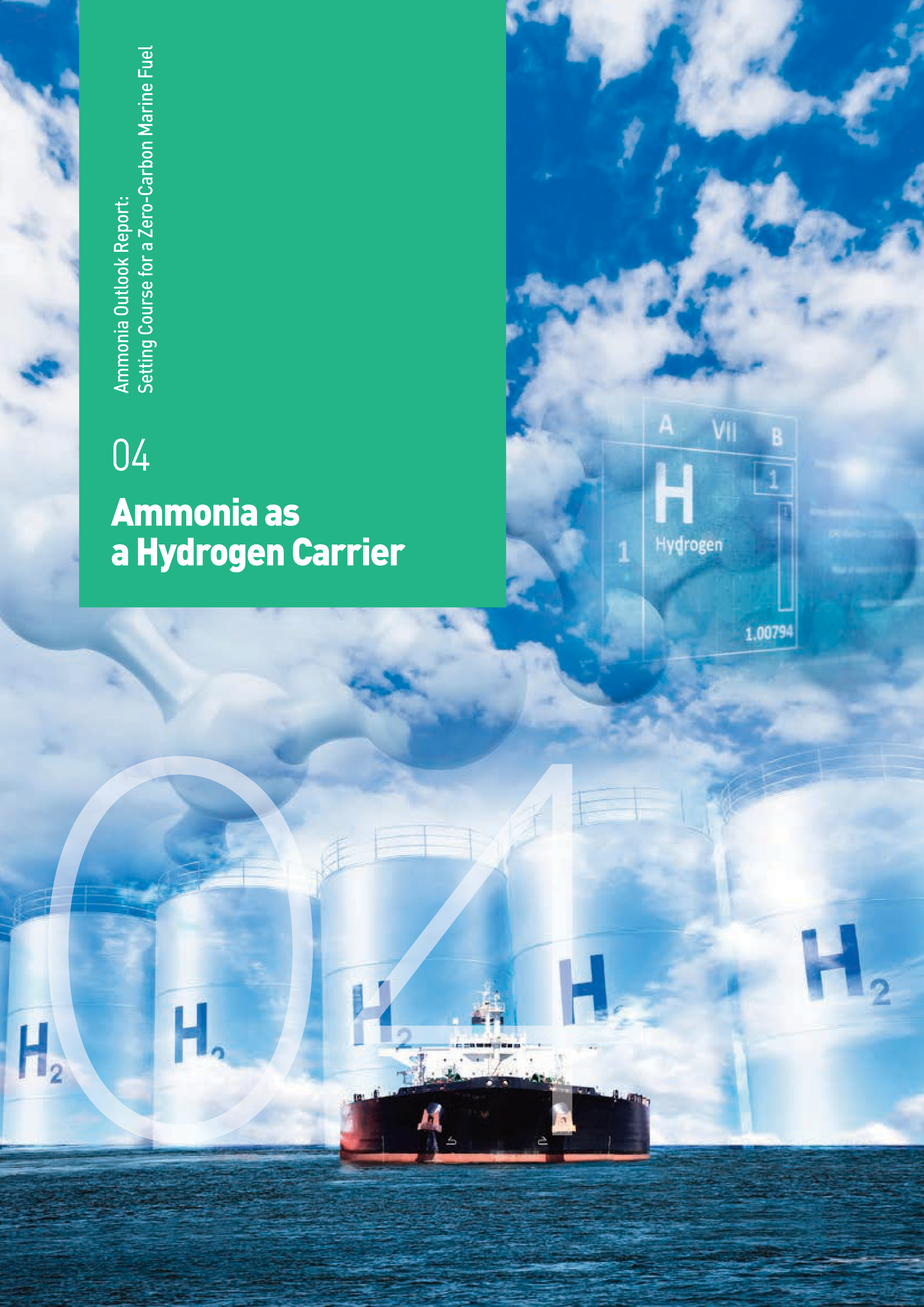
|Fig. 3-11| (Left) Banyan Terminal of Vopak in Singapore[46]; (Right) Strategies for developing supply network for clean ammonia in Japan[47]

|Table 3-4| Outline of progress in ammonia bunkering and terminal projects

Companies (Country)	Project Description
Proton Ventures (Netherlands), Trammo DMCC (UAE), etc.[48]	· Undertaking the construction of green ammonia import terminals for green ammonia imports of up to 2.5 MT at the Port of Rotterdam in the Netherlands. · Committed to an investment of $2 billion for the Pecém Complex in the State of Ceará, Brazil for import of up to 2.5 MT/year of green ammonia to the Port of Rotterdam.
A.P. Møller Maersk (Denmark), Keppel Offshore & Marine (Singapore), etc.[49]	· Entered into an MOU for a joint feasibility study for establishing a green ammonia bunkering hub at the Port of Singapore, the largest bunkering port in the world. · The feasibility study will cover the development of a cost-effective green ammonia supply chain, design of ammonia bunkering vessel, and development of related green ammonia supply chain infrastructure.
RWE (Germany), H2U (Australia)[50]	· Signed an MOU for development of Germany-Australia green hydrogen trading. · The LNG terminal in Brunsbüttel near the coast of the North Sea, Germany, is planned to be utilized as a green ammonia export terminal.
Azane Fuel Solutions (Norway)[51]	· Construction of the first green ammonia bunkering terminal (construction of barge-based or port-based bunkering infrastructure). · Development of an optimized bunkering solution that supplies refrigerated or pressurized clean ammonia from ships, trucks, barges, etc. as fuels to ships.
Royal Vopak (Netherlands), Moda Midstream (U.S.)[52]	· Completed the construction of a terminal for storage and distribution of clean ammonia at the Port of Houston, U.S. · The stored clean ammonia is supplied to Port of Houston, a petrochemical complex, through pipelines, and transported to the customers in the U.S. through railroad infrastructure.
Itochu (Japan), Ube Industries (Japan), etc.[53]	· Signed a joint venture for establishment of ammonia supply hub in Japan and development of ammonia-fueled ships (March 2021) · Itochu is responsible for building an ammonia supply hub in Japan and developing bunkering vessels, Ube Industries is responsible for development of onshore facilities for marine fuel supply, and Uyeno Transtech for developing ammonia bunkering vessels and formulation of their safety standards.

04

Ammonia as a Hydrogen Carrier



4.1 Global Hydrogen Demand

Currently, the refining and petrochemical sectors account for most of the hydrogen demand (hydrogen for desulphurization in refineries/hydrocracking); however, in the near future, it is expected that hydrogen demand will arise in new, emerging sectors and this new demand will continue to increase. New sectors with projected demand for hydrogen can be largely categorized into power generation/mobility/industries.

|Table 4-1| New hydrogen demand in the future

Hydrogen demand	Description
Power generation	Fuel cells for power generation/building
	Hydrogen gas turbine (dual fuel/single fuel)[54]
Mobility	Ground Mobility - Cars, Buses, Trucks, and Special Vehicles
	Marine Mobility - Ships
	Air Mobility - Airliners, Urban Air Mobility
Industry (iron and steel production/refining/ petroleum chemicals/cement)	Direct reduced iron in steel and ironmaking industry
	Alternative of naphtha in the petrochemical sector (benzene, toluene, and xylene/olefin production)
	Alternative fuels for cement kilns

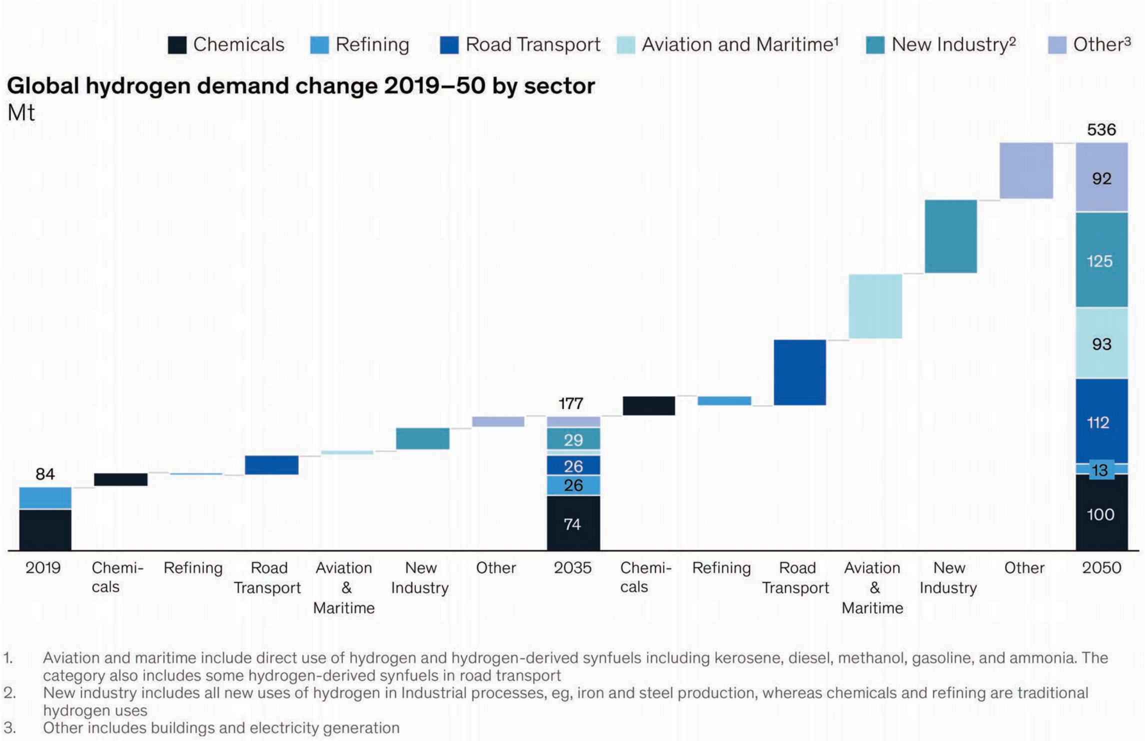
According to the Global Energy Perspective 2022[62] published by McKinsey & Company, the global hydrogen demand, which remained at only 84 MT in 2019, will increase by approximately 110% to 177 MT in 2035, and by 540% to 536 MT in 2050.

According to the Global Hydrogen Review 2021[63] by the International Energy Agency (IEA), under the assumptions of net-zero emissions scenario, global hydrogen demand, which stalled at only approximately 90 MT in 2020, is expected to increase by 230% to approximately 300 MT in 2035 and by approximately 490% to 530 MT in 2050.

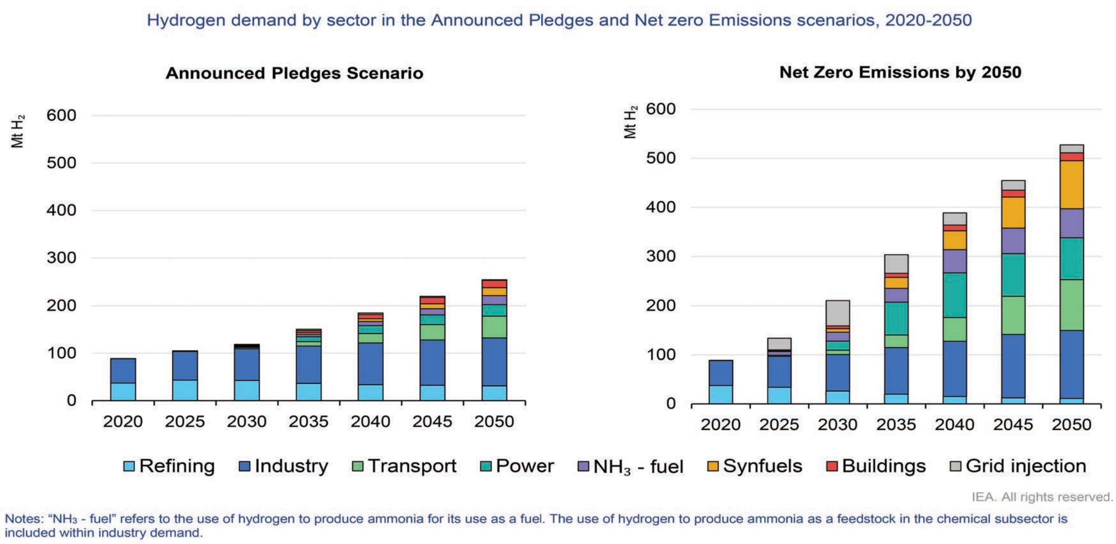
|Table 4-2| Projection of global hydrogen demand (Unit: 1 MT)

Research by/Year	2019/2020	2035(E)	2050(E)
McKinsey	84 (As of 2019)	177	536
IEA	Approx. 90 (As of 2020)	300	530

According to the two reports above, the sector-wise projected global hydrogen demand by 2050 is as follows. In the refining and petrochemical sectors, the traditional hydrogen demand, such as hydrogen for desulphurization in refineries/hydrocracking, is expected to increase by 100 MT by 2050. However, as new types of demand for hydrogen arises in industries such as steel/iron manufacturing and cement, mobility, and power generation, and with the expected explosive growth in such demand after 2035, it is expected that nearly 400 MT of hydrogen will be needed in 2050. The growing hydrogen demand in new sectors will boost the hydrogen economy.



|Fig. 4-1| Projection of sector-wise global hydrogen demand[55]

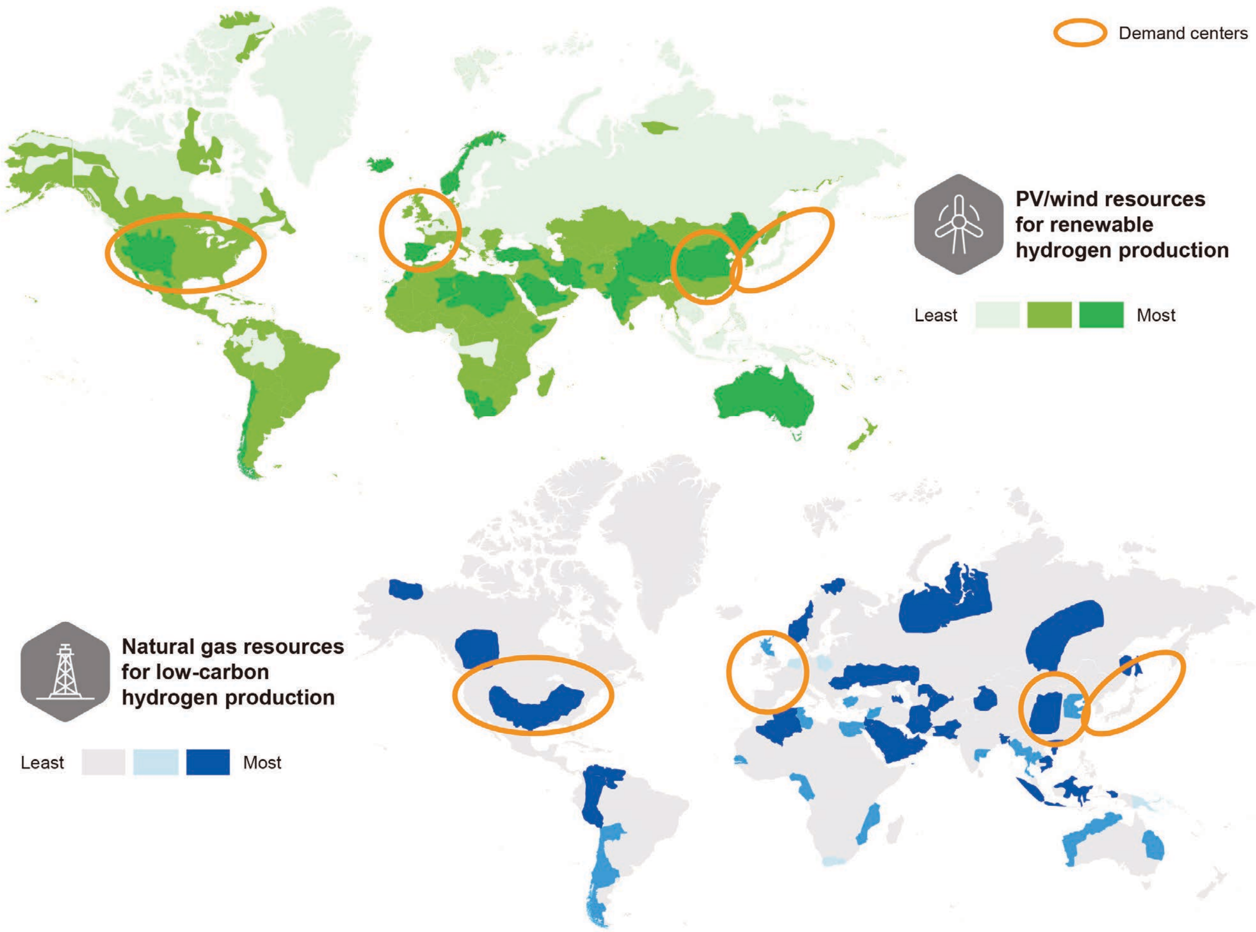


|Fig. 4-2| Projection of sector-wise global hydrogen demand[56]

4.2 Ammonia as a Hydrogen Carrier

4.2.1 Disparity between the major areas of hydrogen demand and hydrogen production

Cost-effective production of clean hydrogen (blue/green hydrogen) will be possible in regions with abundant photovoltaic, wind, and natural gas resources. Fig. 4-3 shows that regions such as Australia, North Africa, and the Middle East are rich in these resources, but they are not centers of hydrogen demand; therefore, hydrogen should be produced in these regions for export purposes.



|Fig. 4-3| Resource distribution for production of clean hydrogen and places of major hydrogen demand[57]

According to the Global Hydrogen Review 2021 of the IEA, South Korea and Japan, which are classified as candidate regions for major demand centers due to lack of resources for clean hydrogen production, will import hydrogen from the aforementioned countries. That is, largescale transportation of hydrogen due to the discrepancy between regions of major hydrogen demand and production is another important matter for consideration.

|Fig. 4-4| Estimated amount of hydrogen imports by 2050 and places of supply for South Korea and Japan[58]

4.2.2 Advantages of ammonia as hydrogen carrier

If intercontinental seaborne transportation of hydrogen is required, ammonia, LH2, and Liquid Organic Hydrogen Carriers (LOHC) can be considered as candidates for hydrogen carriers. The most important characteristic to be considered for largescale seaborne transportation is the volumetric hydrogen storage capacity. Ammonia has a volumetric hydrogen storage capacity of 120 kg_{H2}/m^3, which is the largest when compared to that of LH2 (70.8 kg_{H2}/m^3), LOHC (47.1 kg_{H2}/m^3 based on methylcyclohexane), and methanol (99 kg_{H2}/m^3). Moreover, technical challenges such as a cryogenic cargo containment system that can provide the storage condition of -253 °C and a boil-off gas treatment system must be overcome for the transportation of LH2. However, with the increasing pace of technological development and strong determination of the industry, the LH2 tanker can serve as an efficient means for hydrogen transport in the mid-to-long-term perspective. However, even if the technology development is successful, considering the time required for development and demonstration, sufficient time is required until hydrogen tankers are commercialized and matured to achieve economies of scale. LOHC may be inefficient because it involves continuous shipping of a certain amount of organic compounds for storage and release of hydrogen. Although methanol and LNG are considered as mediums for hydrogen storage, because they are carbon compounds, CO_2 emissions pose difficulties in the process of hydrogen production. Therefore, it is reasoned that ammonia is the most efficient medium for largescale hydrogen storage and transport.

The Global Hydrogen Review[68] published by the IEA in 2022 indicated that the electrolysis plant capacity should increase to promote the expansion of the hydrogen supply chain and projected an increase in the electrolysis capacity from the recent level of 8 GW/y to 60 GW/y by 2030. Such an increase in capacity is expected to reduce the cost of hydrogen production based on renewable energy to the range of 1.3-4.5 USD/kg_{H2} (39-135 USD/KWh) by increasing the price competitiveness of electrolysis plants. Largescale hydrogen trade requires advancement in technologies for hydrogen storage and transportation as well as optimal level of prices. The world's first shipment of LH2 from Australia to Japan occurred in February 2022, marking a key milestone in the development of an international hydrogen trade. According to the hydrogen export-oriented projects discussed above, 12 MT of hydrogen per annum will be exported by 2030, reaching 2.6 MT/year by 2026. Interestingly, the announcement of hydrogen export projects has increased rapidly in the last two years, and most of the projects chose ammonia as the hydrogen carrier. The IEA predicted that further growth of the hydrogen market would hinge on policy development in support of ammonia trade and technology developments.

|Table 4-3| Hydrogen storage capacity against volume for hydrogen carrier candidates

	(Liquid) ammonia	LH2	LOHC (Methylcyclohexane)	Methanol
Hydrogen storage capacity against volume (kg_{H2}/m^3)	120	70.8	47.1	99

4.2.3 Ammonia for industrial-scale production

Ammonia is synthesized through the Haber-Bosch process in which hydrogen produced using various methods reacts with nitrogen obtained from the air separation process. The Haber-Bosch process requires operating conditions of high temperatures ≥ 400 ℃ and high pressure ≥ 200 bar, which requires high energy consumption in the process, but the process allows mass production of ammonia. Owing to the continuous development of catalyst technology in the Haber-Bosch process for almost 100 years, more efficient operation of the process at lower temperatures and pressures led to increasing energy efficiency in the process. As of 2020, the capacity for ammonia plants amounts to the production of 225 MT of ammonia worldwide, and this capacity is expected to increase to approximately 290 MT by 2030.[59] As of 2020, the worldwide production of ammonia reached approximately 180 MT; thus, it is estimated that approximately 45 MT of additional ammonia production is possible.[60] That is, under the circumstance that the current capacity allows sufficient supply of ammonia even when a new demand for ammonia arises.

|Table 4-4| Global overview of the scale of ammonia production facilities and status of utilization (As of 2020)[61]

	China	North America	Middle East	Russia, Central Asia	Europe	South East Asia	Central South America	Africa	Australia	Total
Capacity (million ton)	76.1	24.4	20.5	23.4	26.5	31.2	9.8	10.2	2.3	224.6
Utilization rate (%)	72	91	82	98	69	95	68	96	83	81
Redundant Capacity (million ton)	21	2.2	3.7	0.5	8.1	1.5	3.1	0.4	0.4	40.9

Currently, fertilizer production accounts for most of the ammonia demand; however, if ammonia is used as a hydrogen carrier, the production capacity will need to be increased to meet the demand. Unlike other hydrogen carriers, industrial-scale production of ammonia is facilitated through the Haber-Bosch process, which is a sufficiently mature technology that has been developed over many years, and it is expected that the demand for ammonia as the hydrogen carrier can be sufficiently met by expanding ammonia plants for the new demand.

With active progress on the clean ammonia production projects and increase in the number of countries that plan to export the produced clean ammonia, the demand for ammonia tankers is expected to rise rapidly. Based on the assumption that the ratio of seaborne transportation of ammonia at 10%, which is the current level, and the projected capacity for an ammonia tanker at 130,000 tons, 588 tankers for clean ammonia transport will be needed by 2040, and the number will increase to 1,236 by 2050. To meet the rising future demand for clean hydrogen, ammonia tankers are expected to create a new business area in the shipbuilding industry, with approximately 50 ships projected to be ordered annually from 2030.

Moreover, as discussed above, if the technology enabling the direct use of ammonia as a fuel reaches a commercialization level in the near future, ammonia can be used as a carbon-neutral fuel in the tanker during transportation. Hydrogen production will further increase with ammonia emerging as an important pillar for the hydrogen economy, with its demand for power generation and as petrochemical feedstock and marine fuel. A decrease in the price of hydrogen due to the economies of scale achieved through mass production will also lead to a decrease in the price of clean ammonia, which is synthesized with hydrogen as the key component.

|Table 4-5| Market outlook for clean ammonia carriers

Category	2019	2030(F)	2040(F)	2050(F)
Hydrogen demand (M ton)	71.0	87.2	136.5	287
Ammonia carrier demand (vessel)	306	376	588	1,236

Note) The number of ammonia carriers was estimated based on the following assumptions: ammonia-hydrogen conversion ratio of 5.6, ammonia seaborne transportation ratio of 10%, and predicted ammonia carrier deadweight tonnage of 130,000 ton.

※ Source: Reconstruction of data from IEA and Daishin Securities Research Center

05

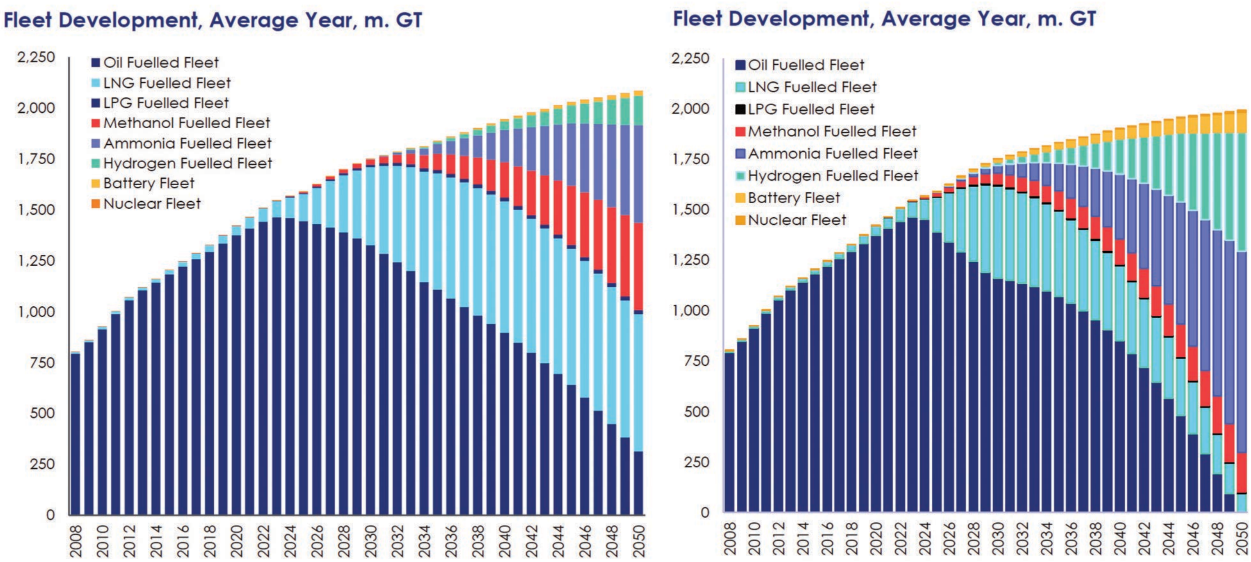
Next-Generation Marine Fuel Outlook

5.1. International Maritime Organization 2050 Decarbonization Strategy

The IMO adopted the Initial IMO GHG Strategy in 2018 with the goal of 50% reduction in GHG emissions by 2050 based on its level in 2008, and this Initial IMO Strategy is to be confirmed and finalized in 2023. However, many countries, which are predominantly from Europe, have proposed that net-zero shipping emissions should be achieved by 2050 instead of by the end of this century; therefore, even more stringent regulation of GHG emissions is expected. Furthermore, the EU has pushed for inclusion of the shipping sector into the ETS as of 2024 through the “Fit for 55” package, and established new FuelEU Maritime regulations to mandate the use of sustainable marine fuel, leading to the implementation of tighter regulations.

In addition to international regulatory agencies such as the IMO and EU, banks that account for more than 50% of the global maritime finance have jointly established CO_2 emission limits for ships as an indicator for making investments in the shipping industry. The Sea Cargo Charter, a global initiative with bulk shippers, and Clean Cargo Working Group, an initiative among container shippers, also use environmental metrics based on CO_2 emissions for signing of charter contracts. Moreover, 350 major global corporations, including Google and Apple, have joined the Renewable Energy 100 initiative, declaring that they will meet 100% of their energy demand with renewable energy. Therefore, for shipping companies, reduction of GHG emissions has rapidly emerged as a matter of survival, not a matter of choice.

Fig. 5-1 shows the data presented by Clarkson Research of the projected global fleet development scenarios when the IMO Initial Strategy is maintained at the current target and when the target is revised to 100% reduction



50% reduction by 2050 100% reduction by 2050

|Fig. 5-1| Global fleet development scenario with respect to GHG reduction scenarios[62]

by 2050. If the Initial IMO Strategy is maintained, the proportion of zero-carbon fuels such as ammonia and hydrogen would account for approximately 31% of the total; however, if the Initial IMO Strategy opts for the higher target, zero-carbon fuels will account for a remarkable proportion of 85% and no fossil fuels such as FO can be observed in the data for the 100% reduction target.

This indicates that even if the efficiency in the shipping industry can be increased through technical and operational measures to reduce GHG emissions, to accomplish the ultimate net-zero target, transition to zero-carbon fuels or carbon-neutral fuels is necessary. Furthermore, to achieve the IMO target by 2050, all technology developments and infrastructure for fuel production needs must be established before 2030. With the IMO raising the target, the transition to zero-carbon fuels is expected to increase its pace. From the perspective of a shipping company, the main issue for fleet composition planning will occur during the transition from conventional fuels such as FO or LNG to zero-carbon fuels such as ammonia and hydrogen. Moreover, in the case of methanol, which is another emerging carbon-neutral fuel, it is significantly important to analyze its advantages and disadvantages against the use of ammonia.

Currently, LNG is the most sought-after marine fuel as a carbon-neutral fuel. LNG-fueled ships are the commonly used means of intercontinental transport for energy. With LNG, largescale production is possible, the supply is relatively easy, and the cost is reasonable for its use as a marine fuel assuming that no unexpected international incidents have occurred such as the Russia-Ukraine war. It also has the advantage for use in conjunction with an onboard CO_2 capture system in the future or mixed with synthetic methane.

As described above, ammonia is highly likely to be used as hydrogen carrier for intercontinental transport and has the advantages such as capabilities of largescale production, price competitiveness, and established supply chain. However, owing to requirements such as the development of an ammonia engine, considerations of corrosiveness and toxicity, and the fact that ammonia is not 100% zero-carbon fuel because of the need for pilot fuels due to its combustion characteristics (if a biofuel can be used as a pilot fuel, then ammonia can be considered as a carbon-free or carbon-neutral fuel), and the possibility of rapid development of technology for the transport of hydrogen by liquefaction, the above merits and advantages may be offset, and therefore, use of ammonia as a fuel has some uncertainties.

The role of carbon tax is significantly important for the fuel transition from LNG to ammonia. The IMO will impose more stringent regulations on the carbon tax until zero-carbon fuels become competitive with existing fossil fuels to achieve the GHG reduction targets.

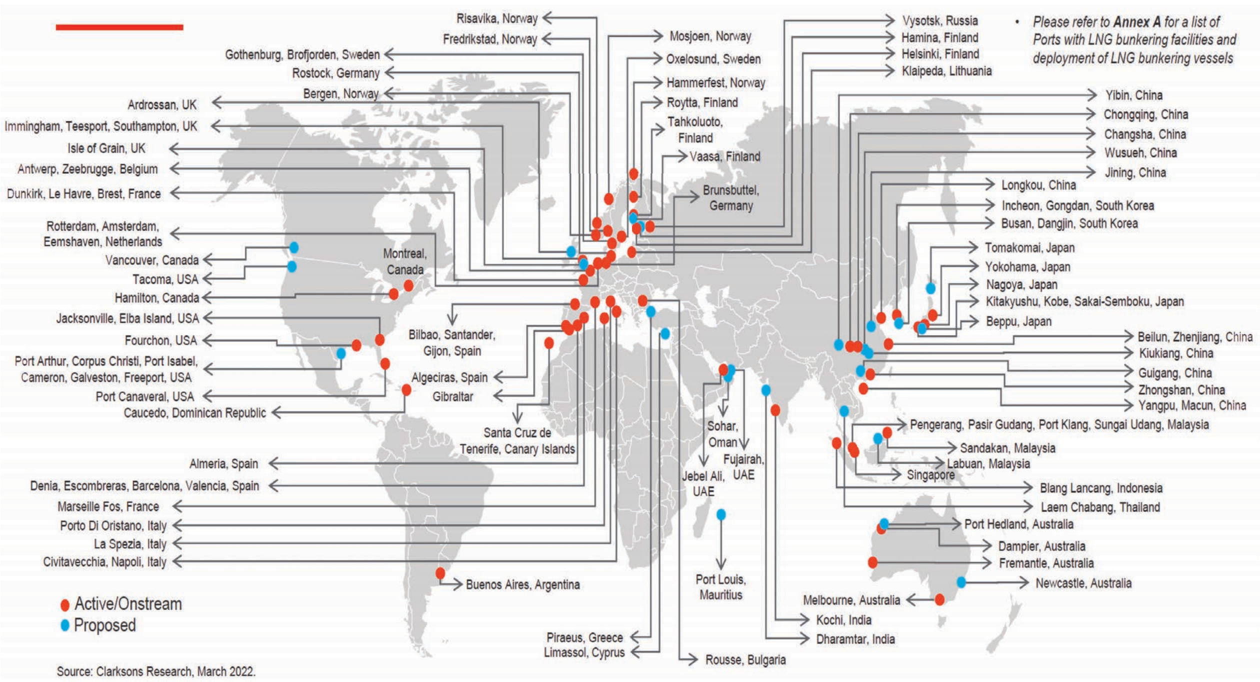
Despite the technical and economic uncertainty of ammonia as a marine fuel and volatility of carbon tax due to IMO regulations, we collected information that is currently available to predict the price of fuels and carbon tax and present an analysis of the timing of the fuel transition from LNG to ammonia. Moreover, we performed comparative analysis of the advantages and disadvantages of bio/green methanol, a representative carbon-neutral fuel and ammonia.

5.2. Fuel Transition: From Liquefied Natural Gas to Ammonia

To satisfy the IMO regulations, rapid transition to zero-carbon fuels is necessary while reducing the use of fossil fuels, including HFO. LNG has attracted attention as a low-carbon fuel that can serve as a bridge for the transition from oil-based to zero-carbon fuels. The supply infrastructure for LNG is well established, has high energy density, and LNG fuel tanks and internal combustion engines that can be used on ships have already been developed. By using LNG instead of oil-based fuels, pollutants such as SO_x, NO_x, and particulate matter and CO_2 emissions can be reduced. Thus, the number of LNG-powered ships has been rapidly increasing. However, in the long run, it has the disadvantage of being produced from fossil fuels with CO_2 emissions; therefore, when comparing the short- (2030) or long-term (2050) perspectives, the role of LNG as a marine fuel exhibits controversial results.[63]

Maritime Strategies International estimates that, by 2025, the share of LNG in the marine fuel market will be 2%, and assuming that all LNG-ready ships use LNG, the market share will increase to 3% by 2030, and 10-11 MT of LNG per annum will be used as marine fuel.[64] This is an analysis based on various decarbonization scenarios rather than the order of LNG ship deliveries, and may differ from reality. A report published by Clarksons Research acknowledges that although LNG-powered ships are increasing significantly, questions remain as to whether they will serve as a long-term solution for the environmental regulations of the IMO. The reason for addressing the uncertainty is that there are different assumptions on the market penetration of LNG as a low-carbon fuel, and in particular, the ratio may differ depending on the level of technology development such as an increase in efficiency. In 2018, UMAS presented the following four scenarios on the LNG market penetration projection:[63] High gas: LNG market penetration of 61% due to low LNG prices coupled with significant carbon offsetting regulations, 2) Transition: LNG market penetration of 11% due to increased use of hydrogen and limited use of carbon regulations, 3) Limited gas: Higher LNG prices and biofuel availability leads to LNG market penetration of 3%, 4) Business as Usual: LNG market share reaches 25% in case of non-compliance with IMO decarbonization regulations. That is, as regulations on carbon emissions are tightened, the LNG market share is predicted to decrease due to its limitations, and the proportion of zero-carbon fuels such as biofuel and hydrogen will increase to a significant extent. However, this scenario is based on the assumption that the market penetration of zero-carbon fuels and technology development related to those fuels will show smooth progress by 2050; in the meantime, many stakeholders predict that LNG will sufficiently fulfill its transitional role.

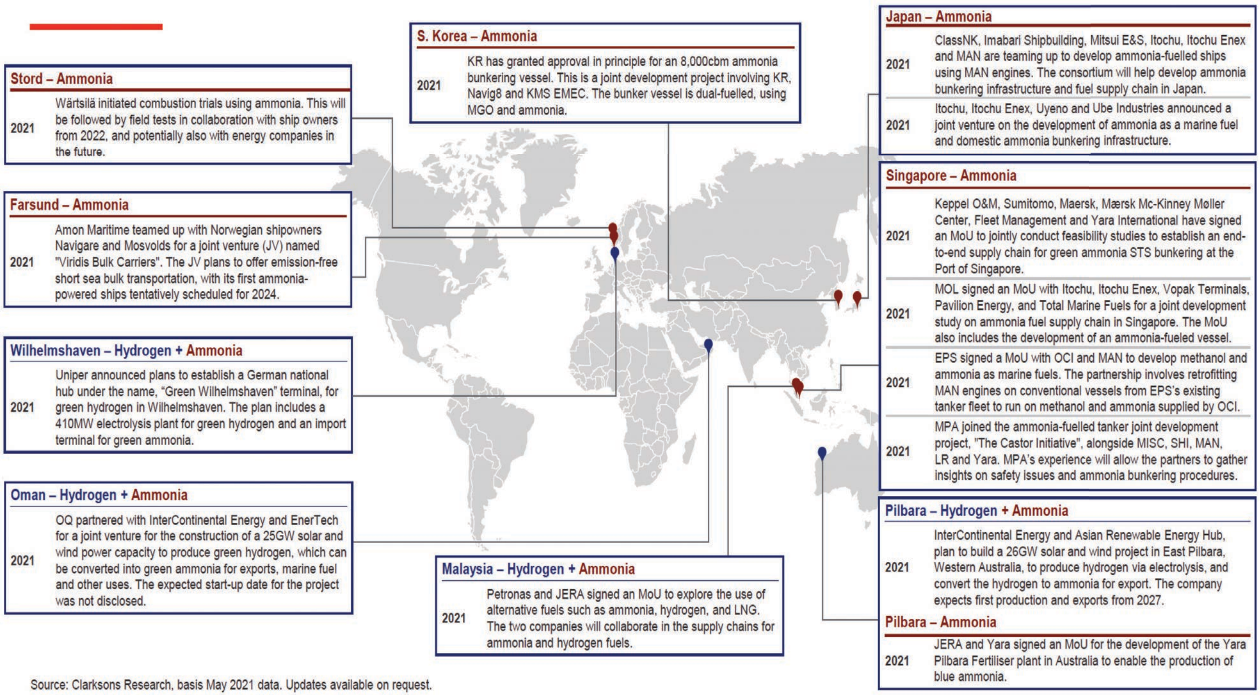
Based on the recent trend of the global economy, the use of LNG has been increasing. From the sector-wise natural gas demand in 2020, the power generation sector accounts for 40%, followed by the industrial sector at 22%, and the household/commercial sector at 19%, while the market share for the marine fuel is only 1%. However, from the perspective of the need for LNG bunkering infrastructure for its utilization as a marine fuel, the active trade of LNG in the energy market is a positive factor. Fig. 5-2 shows that as of 2021, there are 30 LNG bunkering units in operation around the world, 139 ports capable of LNG bunkering, and 88 ports under construction. Currently, ports capable of LNG bunkering are predominantly distributed in Europe, but investments in bunkering facilities are in progress in East Asian countries such as South Korea, Japan, and China. Bunkering facilities for supplying LNG as a marine fuel are under construction around countries where LNG trade is active. Therefore, considering the prospect of technology development and infrastructure construction for utilizing LNG as marine fuel, the share of LNG is expected to increase in the short term.[64]



|Fig. 5-2| Country-wise liquefied natural gas (LNG) bunkering ports [65]

Although the growth of LNG is remarkable in the short term, LNG as a fuel has a limited effect with respect to CO_2 emissions. Therefore, ammonia, which is a zero-carbon fuel and has advantages in terms of transportation and application, has attracted increasing attention. As previously discussed, the production of ammonia is estimated to be in the scale of 180 MT for the fertilizer industry in China, Russia, and the U.S, with an established supply chain across the globe. As the demand for ammonia is increasing in the petrochemical and power generation sectors as well as in the fertilizer industry, ammonia production capacity and supply infrastructure are projected to be further expanded as shown in Fig. 5-3.

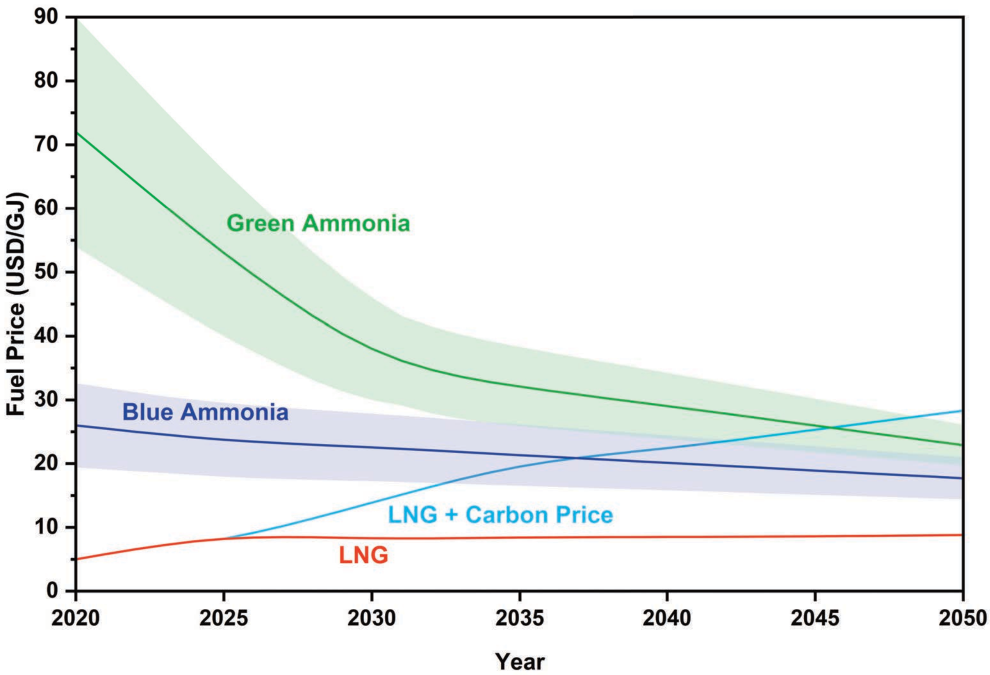
Fig. 5-3 shows that many of the ammonia production projects are implemented with renewable hydrogen projects. The hydrogen required for ammonia synthesis is currently supplied through methane steam reforming; however, if it can be supplied from water electrolysis using renewable electricity, then the expected decrease in electricity cost based on renewable energy will lead to beneficial results.[67] Gray ammonia, obtained from coal gasification, is more expensive than low sulfur fuel oil (LSFO); consequently, the market penetration of gray ammonia is predicted to be difficult at present. For ammonia to penetrate the market as a marine fuel, infrastructure



|Fig. 5-3| Country-wise progress and schedule of ammonia bunkering facility development[77]

for ammonia production and supply must be expanded, and fuel tanks, FSSs, and engine technologies necessary for powering ships must be developed. Blue ammonia involves CO_2 emissions at the production stage, and thus, the decision on imposing a carbon tax will have an impact on the price of blue ammonia, while electricity costs generated from renewable energy sources will have a significant impact on the production cost of green ammonia. As presented in Chapter 3, blue ammonia production costs are expected to range from 18.8 to 26.3 USD/GJ by 2030, reaching 13.4 to 22.0 USD/GJ by 2050. The cost of green ammonia production is estimated to be in the range of 21.3-49.0 USD/GJ in 2030, but will decrease to 14.8-31.0 USD/GJ as electricity costs continue to fall owing to the use of renewable energy sources. From a mid-to-long-term perspective, clean ammonia is considered as the most attractive fuel for the decarbonization strategy.

The price projection for clean ammonia and LNG when considering the carbon tax as well as the fuel price is shown in Fig. 5-3. Carbon tax has a significant impact on fuel-related operating costs, and if a carbon tax is applied to LNG-fueled ships, fuel costs will continue to rise. It is assumed that a carbon tax of 100 USD/ton_{CO2} will be applied in 2030, followed by 200 USD/ton_{CO2} in 2035, 250 USD/ ton_{CO2} in 2040, 300 USD/ ton_{CO2} in 2045, and 350 USD/ ton_{CO2} in 2050. Fig. 5-4 shows that the fuel price of green ammonia is expected to decrease, while the price of LNG with the application of carbon tax shows a gradually increasing trend. Therefore, the price of blue ammonia will become similar to that of LNG by 2035-2040, and the crossover where the price of green ammonia becomes cheaper than that of LNG will occur in 2042-2048. This indicates that, in the projection, with a continuous decrease in green ammonia production cost due to the increasing carbon tax, the use of ammonia as fuel is more advantageous in terms of fuel price from around 2045. The introduction of a carbon tax is imperative to narrow the operating cost difference between ships powered by conventional fossil fuels and those powered by zero-carbon fuels. That is, to reduce GHG emissions from the use of fossil fuels, a policy that promotes the use of zero-carbon fuels by setting a high carbon tax on fossil fuels may be implemented.



|Fig. 5-4| Projection of fuel prices: LNG, blue, and green ammonia (Carbon tax applied)

5.3. Methanol as Marine Fuel

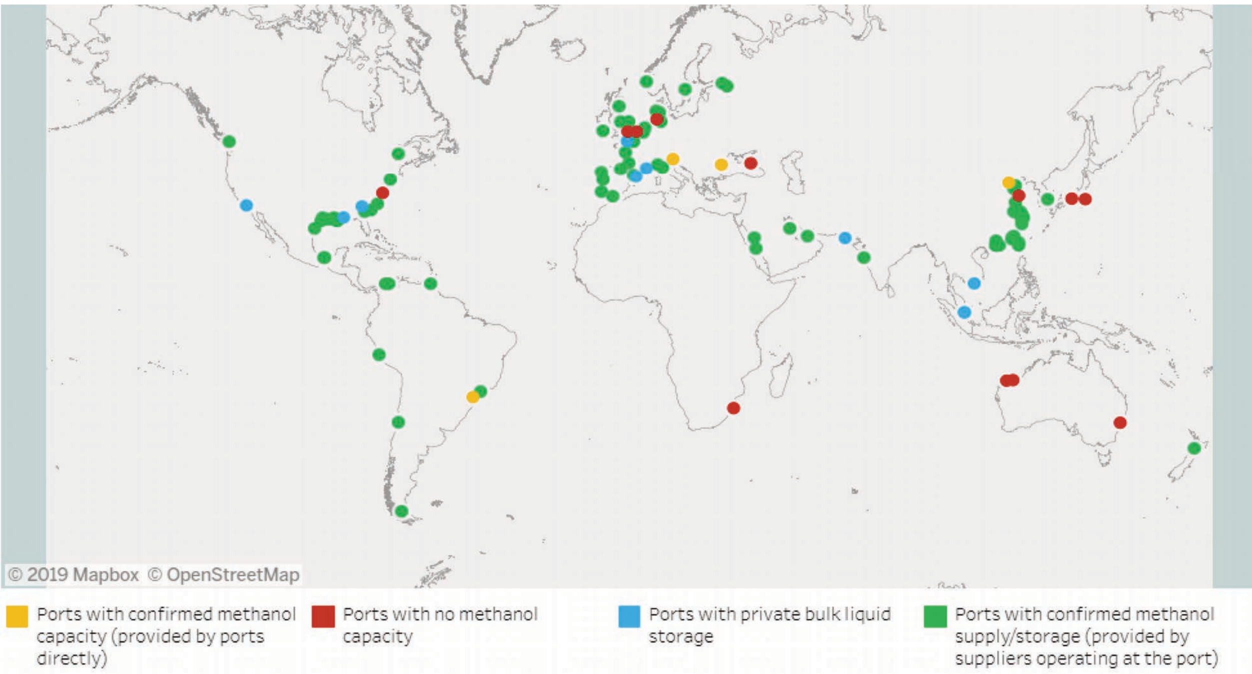
The global methanol production is currently 98 MT, and 90 methanol plants are in operation worldwide. The methanol produced from plants is mostly used as intermediates in the petrochemical industry, and some of the methanol is mixed with gasoline for trade. Therefore, using methanol as a marine fuel has the advantage of leveraging the already established methanol production and supply infrastructure and does not require special technology development for bunkering. However, methanol, which had attracted attention as a next-generation fuel, will be limited to renewable resources-based methanol. Currently, methanol is produced from natural gas and has 25% less CO_2 emissions as compared to that of HFO. However, considering the life cycle assessment of HFO and methanol, the CO_2 emission from methanol can increase by 10%; therefore, only renewable methanol has a true value as a next-generation fuel.

However, the maturity of the renewable methanol production technology remains at the technology readiness level 3. Renewable methanol is classified into e-methanol produced using electricity and CO_2 and bio-methanol produced using biomass gasification or by reforming the biogas obtained from biomass. CO_2 for e-methanol should be supplied at cheap prices from a collection source linked with CCS or supplied through direct air separation; moreover, for bio-methanol, biomass raw material must be purchased in large quantities at cheap prices for gasification. Renewable methanol is expected to be supplied for marine fuel from 2035, and bio-methanol, in particular, is expected to account for more than 2% of the total marine fuel. The current cost level of fossil fuel-based methanol production ranges from 5.0 to 12.6 USD/GJ. The cost of CCS-integrated e-methanol is predicted to range from 40.2 to 80.4 USD/GJ, and that of bio-methanol is predicted to range from 16.1 to 38.7 USD/GJ.[68] Although green methanol prices are significantly more expensive than fossil fuel-based methanol, they will gradually fall, reaching the price range of 29.7 to 40.3 USD/GJ in 2050. As the production cost of methanol is more than twice that of LSFO, incentives must be applied for its market penetration. Therefore, the primary factors limiting the potential of methanol as a marine fuel are the development of an effective supply chain, expansion of production scale, and securing resources for raw materials.

Currently, methanol bunkering is possible at nearly 90 of the top 100 ports worldwide, including Singapore, Algeciras, Houston, and Rotterdam, and the conventional diesel oil tanks can also store methanol with minimal modifications, resulting in easier bunkering when compared to that of other alternative fuels.[69] Earlier this year, the Gothenburg Port Authority, Sweden, announced regulations on ship-to-ship bunkering of methanol and announced ambitious plans to become the primary bunkering hub for green methanol in Northern Europe.[70] Moreover, in South Korea, which is not a methanol-producing country, two methanol-fueled tankers built by Proman Stena Bulk, a joint venture between the Swiss methanol producer Proman and Swedish shipping company Stena Bulk, have become the first vessels to bunker methanol in South Korea, each with over 2,000 tons of methanol during the bunkering operation.[71]

That is, bunkering infrastructure has already been established for methanol, but securing green methanol production is the key. In the case of using electricity from renewable sources, the problem of mass production due to plant capacity limitation is highlighted as an obstacle, whereas in the case of bio-methanol, an infrastructure that can securely provide feedstock is required. Moreover, as the EU has decided not to include palm oil in biofuels, the issue of securing feedstock has become even more challenging. Although the carbon source required for methanol synthesis needs to be linked with CCS projects, CO_2 value chains have not been established with commercial CCS projects worldwide. Thus, going forward, close monitoring is required on the trend of the increase in methanol production.

There are many advantages of using methanol as marine fuel: methanol-fueled engines have been already developed and storage of methanol at ambient temperatures is also possible. However, from the perspective of life cycle assessment: Well-to-Tank perspective, it is unclear whether methanol is a carbon-neutral fuel because the engine has CO_2 emissions. The commercialized methanol synthesis process currently available is to obtain methanol through a catalytic reaction of synthetic gas (syngas) consisting of carbon monoxide and hydrogen. Syngas can be obtained through steam reforming or coal gasification. Recently, with the development of a direct



|Fig. 5-5| Infrastructure for methanol across major global ports[72]

CO_2 hydrogenation process that involves the direct reaction of CO_2 with hydrogen, methanol is synthesized using a copper-zinc catalyst under the conditions of a 3:1 ratio of hydrogen and carbon dioxide and pressure and temperature of 70 bar and 250 °C, respectively. Therefore, for qualifying methanol as a carbon-neutral fuel, hydrogen required for methanol synthesis must be obtained from renewable energy, and CO_2 must be obtained from bio sources, not fossil fuels. Methanol applications are limited when compared to those of ammonia. In contrast to ammonia, which is attracting attention as a hydrogen carrier, methanol is less competitive in this aspect. The technological maturity for mass production of methanol is still low.

However, if first movers such as Maersk, CMA CGM, and Hyundai Merchant Marine decide to use methanol as a marine fuel, and many latecomers join the decision, the mass production of methanol may become possible. Considering these points, mutual discussions and cooperation are prerequisites for running of sustainable shipping business by shipping companies worldwide from the perspective of marine fuels.

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