Forecasting the Alternative Marine Fuel

Ammonia

KOREAN REGISTER

R&D Division


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I Background and Necessity

1 IMO's Adoption of Initial Strategy to Reduce Greenhouse Gas

According to the Third IMO GHG Study 2014 by the International Maritime Organization (IMO), the international shipping emitted 796 million tons of carbon dioxide in 2012, and it accounted for 2.2% of the total carbon dioxide emissions worldwide. Although the carbon dioxide emissions by international shipping is not included in the national emission statistics and reduction regulations, it is larger than the total emissions by Germany (755 million tons, 2012), the world's sixth-largest carbon dioxide emitting country. Moreover, interest in greenhouse gas (GHG) reduction has increased worldwide since the conclusion of the Paris Agreement in 2015, and the international community is urging the international marine industry to reduce carbon dioxide emissions to prevent global warming.

The regulations related to GHG include the Energy Efficiency Design Index (EEDI) and the Ship Energy Efficiency Management Plan (SEEMP). The SEEMP has no regulation for actual implementation and, the EEDI is a performance indicator of new ships and thus has a limitation of directly regulating the emissions of GHG, which is emitted during actual ship operation.

According to the "Regulation (EU) 2015/757 on the monitoring, reporting, and verification of carbon dioxide emissions from maritime transport" that went into force on July 1, 2015, the EU obligates vessels with a total gross tonnage of 5,000 tons or more to report information on carbon dioxide emission, navigation time and distances, and cargo transport volume when they touch at EU ports. Its purpose is to determine GHG emissions from international shipping in order to strengthen GHG regulation in the future.

Moreover, IMO adopted the resolution MEPC.278 (70), which mandated a ship fuel data collection system to record and report the vessel's fuel consumption at its 70th MEPC Meeting in October 2016. As such, a vessel with a total gross tonnage of 5,000 tons or more in international marine navigation must report its fuel consumption annually, and it is expected that total carbon dioxide emissions from internationally navigating vessels can be determined from the data.

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IMO's Roadmap to Reduce GHG (2016 - 2023)

▶ **October 2016 (MEPC 70)**
Adopted the "Data collection system" and approved the "Roadmap"

▶ **April 2018.04 (MEPC 72)**
Adoption of the Initial IMO Strategy
(Short-, mid-, and long-term further measures with possible timelines)

▶ **January 2019**
Start of Phase 1: Data collection

▶ **Spring 2019 (MEPC 74)**
Initiation of the 4th IMO GHG Study (Using the data for 2012 - 2018)

▶ **Summer 2020**
Data for 2019 to be reported to IMO

▶ **Autumn 2020 (MEPC 76)**
Start of Phase 2: Data analysis (no later than Autumn 2020)
& Publication of the 4th IMO GHG Study

▶ **Spring 2021 (MEPC 77)**
Beginning of the revision of the Initial IMO Strategy based on the collected data & Reporting of the 2019 data summary

▶ **Summer 2021**
Data for 2020 to be reported to IMO

▶ **Spring 2022 (MEPC 78)**
Phase 3: Decision and report of the 2020 data summary

▶ **Summer 2022**
Data for 2021 to be reported to IMO

▶ **Spring 2023 (MEPC 80)**
Adoption of the revised IMO Strategy
(Short-, mid-, and long-term further measures, as required, with implementation schedules)
& Reporting of the 2021 data summary

IMO adopted the initial strategy for GHG emission reduction from vessels at the 72nd MEPC meeting held in April 2018. The members agreed to the following for the emission reduction target and schedule.

- **Carbon intensity of the ship to decline through implementation of further phases of the energy efficiency design index (EEDI) for new ships**
  Review intended to strengthen the design requirements for energy efficiency by determining the suitable improvement rate in each stage for each ship type
- **Carbon intensity of international shipping to decline**
  Efforts to reduce carbon dioxide emissions per average transport work of international shipping by 40% by 2030 and 70% by 2050 compared to 2008
- **GHG emissions from international shipping to peak and decline**
  To reach the peak of GHG emissions from international shipping as soon as possible and reduce annual emissions by 50% or more by 2050 compared to 2008

The initial strategy includes the candidate short-term, mid-term, and long-term measures to achieve the above GHG reduction targets, and they will be finalized when the final strategy is adopted in 2023. The long-term measures (2030 - 2050) for GHG emission reduction include “To seek the development and supply of zero-carbon or non-fossil fuel,” which implies that the change of ship fuel is essential in the long term.

2 Need for Alternative Ship Fuel

The IMO members have implemented technical measures such as enlargement of ship size and increasing efficiency through the hull form design and propulsion system to meet the EEDI regulation, which is enforced to reduce GHG emissions from ships. Such technical implementations are likely to continue since the EEDI regulation is expected to continue to be strengthened in the future. However, the expected amount of further GHG emission reduction is not high since many technical implementations have already been applied. Another GHG reduction method is operational measures. Since the fuel consumption of a ship rapidly increases as the speed of the ship increases, the slow steaming is one of the most effective ways of reducing carbon dioxide emissions. The shipping industry has already been reducing the operation speed to save fuel consumption, and the effectiveness of low-speed operation has sufficiently been proved. Maersk Line reduced the engine load by about 10% and realized the 10 - 30% reduction of fuel cost and carbon dioxide emissions[1]. However, lowering the speed of a ship reduces the transport volume of the ship, and the shipping company may be forced to add ships to transport freights in time, leading to the additional investment cost. Moreover, prolonged low-speed operation below the minimum engine load of a ship can adversely affect the engine. Since there is a limit to lowering the engine load, the complete decarbonization is not feasible.

[Short-term, Mid-term, and Long-term Measures for IMO's Initial Strategy to Reduce GHG]

Short-term (2018 – 2023)

- Further improvement of the existing energy efficiency framework with a focus on EEDI and SEEMP, taking into account the outcome of the review of EEDI regulations;
- Develop technical and operational energy efficiency measures for both new and existing ships, including consideration of indicators in line with the three-step approach that can be utilized to indicate and enhance the energy efficiency performance of shipping, e.g. Annual Efficiency Ratio (AER), Energy Efficiency per Service Hour (EESH), Individual Ship Performance Indicator (ISPI), Fuel Oil Reduction Strategy (FORS);
- Establishment of an Existing Fleet Improvement Programme;
- Consider and analyse the use of speed optimization and speed reduction as a measure, taking into account safety issues, distance travelled, distortion of the market or to trade and that such measure does not impact on shipping's capability to serve remote geographic areas;
- Consider and analyse measures to address emissions of methane and further enhance measures to address emissions of Volatile Organic Compounds;
- Encourage the development and update of national action plans to develop policies and strategies to address GHG emissions from international shipping in accordance with guidelines to be developed by the Organization, taking into account the need to avoid regional or unilateral measures;
- Continue and enhance technical cooperation and capacity-building activities under the ITCP;
- Consider and analyse measures to encourage port developments and activities globally to facilitate reduction of GHG emissions from shipping, including provision of ship and shore-side/on-shore power supply from renewable sources, infrastructure to support supply of alternative low-carbon and zero-carbon fuels, and to further optimize the logistic chain and its planning, including ports;
- Initiate research and development activities addressing marine propulsion, alternative low-carbon and zero-carbon fuels, and innovative technologies to further enhance the energy efficiency of ships and establish an International Maritime Research Board to coordinate and oversee these R&D efforts; To promote IMO's continuous efforts to reduce atmosphere pollutants
- Incentives for first movers to develop and take up new technologies;
- Develop robust lifecycle GHG/carbon intensity guidelines for all types of fuels, in order to prepare for an implementation programme for effective uptake of alternative low-carbon and zero-carbon fuels;
- Actively promote the work of the Organization to the international community, in particular, to highlight that the Organization, since the 1990's, has developed and adopted technical and operational measures that have consistently provided a reduction of air emissions from ships, and that measures could support the Sustainable Development Goals, including SDG 13 on Climate Change; and
- Undertake additional GHG emission studies and consider other studies to inform policy decisions, including the updating of Marginal Abatement Cost Curves and alternative low-carbon and zero-carbon fuels.

Mid-term (2023 – 2030)

- Implementation programme for the effective uptake of alternative low-carbon and zero-carbon fuels, including update of national actions plans to specifically consider such fuels;
- Operational energy efficiency measures for both new and existing ships including indicators in line with three-step approach that can be utilized to indicate and enhance the energy efficiency performance of ships;
- New/innovative emission reduction mechanism(s), possibly including Market-based Measures (MBMs), to incentivize GHG emission reduction;
- Further continue and enhance technical cooperation and capacity-building activities such as under the ITCP; and
- Development of a feedback mechanism to enable lessons learned on implementation of measures to be collated and shared through a possible information exchange on best practice.

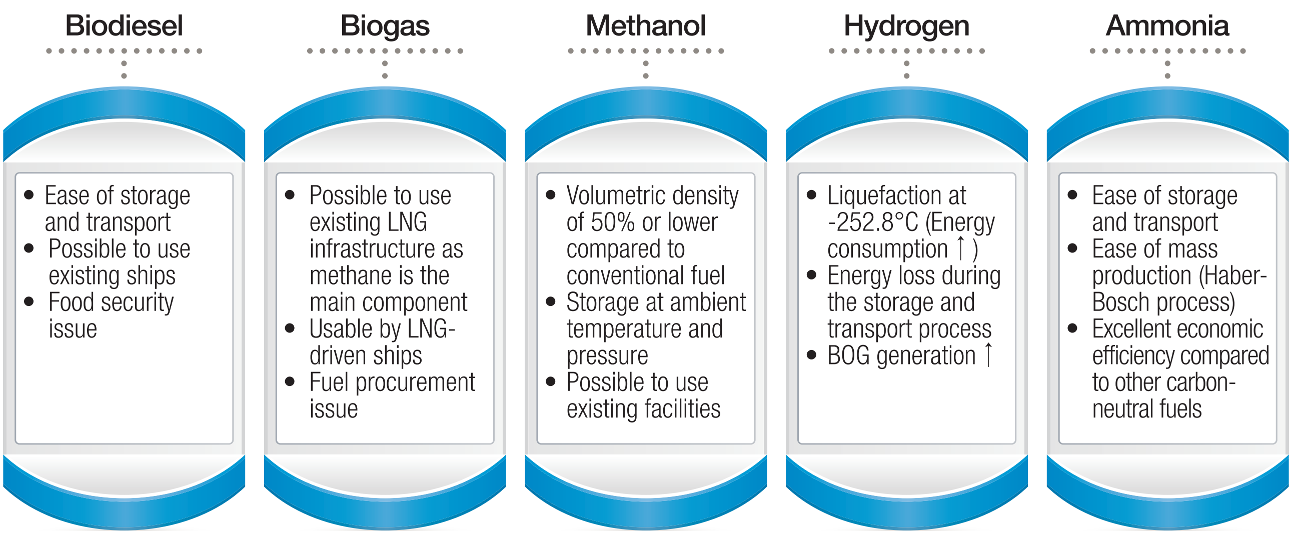
Long-term (2030 – 2050)

- Pursue the development and provision of zero-carbon or fossil-free fuels to enable the shipping sector to assess and consider decarbonization in the second half of the century; and
- Encourage and facilitate the general adoption of other possible new/innovative emission reduction mechanism(s)

The last method of reducing carbon emissions from ships is to use alternative fuels that emit less carbon dioxide. LNG fuel, in particular, has gained attention as the next-generation clean fuel for the ship since it can meet the sulfur regulation in 2020 and reduce fine dust and carbon dioxide. Although only LNG carriers used the boil-off gas (BOG) generated internally as the fuel in the past, more ships that are not LNG carriers are also using LNG as fuel for its eco-friendliness. Moreover, LNG has abundant reserves worldwide, such as shale gas produced in the United States, and it can be supplied stably as a marine fuel like existing fossil fuels. Although there is currently a shortage of LNG bunkering infrastructure facilities to supply fuel to ships, more facilities are being constructed. However, since LNG is a fossil fuel that emits carbon dioxide, it has limitation to achieve full decarbonization (can reduce about 20% of GHG). Therefore, despite the technical and operational measures, it is essential to replace fossil fuel to carbon-neutral fuel to achieve complete decarbonization in shipping in the long term.

A carbon-neutral fuel refers to the fuel that emits zero carbon during the fuel production and consumption processes. The leading carbon-neutral fuels include biodiesel, bio-gas (methane), hydrogen, methanol, and ammonia. The carbon dioxide emissions by biofuels are 0 from the fuel lifecycle viewpoint since the biomass used for fuel production, i.e., plants, absorbed carbon dioxide. It is possible to produce hydrogen, methanol, and ammonia using renewable energy sources and carbon dioxide extracted from the atmosphere. When using natural gas to produce them, the emission of carbon dioxide can be prevented by capturing carbon. The carbon dioxide emissions by such carbon-neutral fuels are entirely determined by the fuel production process, not by ship operations. It is possible to produce carbon-neutral fuels with power generated from renewable energy, such as solar energy and wind energy, which is increasing worldwide. Therefore, it is essential to use the carbon-neutral fuels to decarbonize maritime industry in the long term.

Unlike existing fossil fuels (HFO, MDO, and MGO), there is a wide range of carbon-neutral fuels, as shown in Figure 1, and the characteristics of each fuel are quite different. As such, it is necessary to compare the characteristics of the fuel types. Therefore, this document intends to review ammonia by 1) quantitatively and qualitatively analyzing its characteristics as fuel, 2) summarizing and outlining the related technology and trend, and 3) reviewing the potentiality of its becoming a ship fuel.



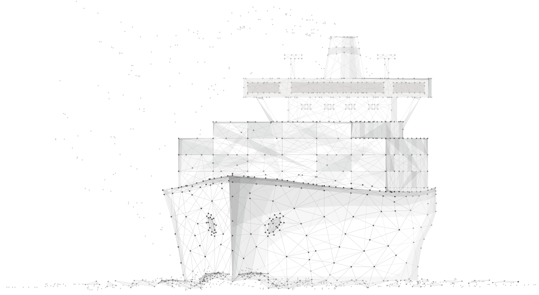
[Figure 1] Leading Carbon-Neutral Ship Fuels

*Source[2]

	Reduction Method	CO_2 Reduction	Remarks
Hull design	Vessel size	18.9%	The efficiency of ships has been increasing using these methods until now. However, there is a limit to further reducing the potential because the technology is already mature.
	Hull shape	15.7%	
	Lightweight materials	5.7%	
	Air lubrication	5.7%	
	Resistance reduction devices	5.6%	
	Ballast water reduction	8.6%	
	Hull coating	1.6%	
Power & Propulsion system	Hybrid power & propulsion	5.5%	There is a limit to CO_2 reduction.
	Power system & machinery	5.5%	
	Power efficiency devices	5.4%	
	Waste heat recovery	8.4%	
	On board power demand	1.0%	
Alternative fuels	LNG	20.4%	The methane slip can partially offset the GHG reduction, and there is a limit to CO_2 reduction since it is a fossil fuel.
	Biofuels	0 - 100% The amount of reduction is determined by the process of fuel production	There is a risk of supply instability due to food security.
	Ammonia		The amount of reduction is high, and the technical barrier to applying it to ships is low.
	Methanol		It requires excessive energy for fuel production.
	Hydrogen		The amount of reduction is high, and the fuel can be produced from renewable energy. However, the technical barrier to applying it to ships is very high (storage temperate and low energy density).
	Battery		Its use is limited due to the low energy density of the battery.
Alternative energy sources	Wind power	12.7%	It can be applied only to some ship types, and it is difficult to source stable energy.
	Solar power	3.8%	
	Fuel cells	6.7%	It is not yet mature technically or commercially.
	Cold ironing (Shore-to-Ship power)	5.1%	The amount of reduction is not high since the power is available only when the ship is berth.
Operation	Speed optimization	19.7%	Although the methods are considered as the important reduction means since they are currently feasible, they alone cannot meet the reduction target.
	Capacity utilization	23.9%	
	Voyage optimization	7.2%	
	Other operational measures	3.6%	

[Figure 2] Reducing Carbon Dioxide Emission from Ships

II International Technology Trend



1 Engine Technology Companies

MAN Energy Solutions(MAN ES)

The company is the most active in the ammonia fuel engine for ships. They introduced the ME - LGIP engine that uses LPG as fuel in 2018, and expect that it is possible to develop an ammonia engine based on ME - LGIP in the future. MAN ES is known to be working with ship registrars, including DNV GL, ABS, and BV, as well as an anonymous ship owner to use ammonia for fuel. MAN ES announced in 2019 that it plans to deduce the results of its study on the risk assessment of ammonia by the middle of the year and to officially request approval by flag states and a partial revision of the protocol for ammonia fuel for ships by the end of 2019[3]. The company is very confident of the development of the ship engine using ammonia fuel and expects to take the lead in future ammonia engine market after the approval by flag states and the revision of the IGC Code and IGF Code..

Wärtsilä

Like MAN Energy Solutions, the company recognizes ammonia as the fuel for ships and is preparing to take action regarding this. It signed a MOU with LUT University of Technology and Nebraska Public Power District in November 2018 to apply alternative fuels, such as ammonia, methanol, and dimethyl ether (DME) to power generator engine[4]. It recognizes the difficult technical barriers, such as low energy density and extremely low storage temperature, of hydrogen but still argues that ammonia, which can be synthesized using hydrogen, is a potential fuel for ships[5]. In June 2019, it formed a consortium with five companies for Zero Emission Energy Distribution at Sea (ZEEDS) and led the effort to construct an ecosystem for ammonia as the fuel for ships According to ZEEDS, it can install 75 large wind turbines in major port hubs to produce ammonia, store it in an offshore structure, and supply the ammonia fuel to about 65 ships daily [6].

J-ENG

In September 2019, J-ENG (Japan Engine Corporation) announced that it launched a new R&D program jointly with the National Maritime Research Institute (NMRI) to develop an engine using carbon-neutral fuel[7]. NMRI conducted research about a 7.7 Kw single-cylinder diesel engine that uses the diesel-ammonia mixture fuel (20% ammonia based on energy) and an exhaust gas post-processing device (SCR) that can reduce N_2O, NOX and unburned ammonia[8]. The cooperation of J-ENG and NMRI is expected to lead to the development of a commercialized ammonia engine for ships.

2 Ammonia Manufacturers

Ammonia is mostly produced using the hydrogen obtained by reforming natural gas, and the cases of producing hydrogen using renewable energy for carbon-neutral ammonia production have increased[9].

The Australian Renewable Energy Agency (ARENA) is sponsoring the planned construction of a plant that produces green ammonia with renewable hydrogen in Queensland. Darren Miller, the CEO of ARENA, expects the project to promote the use of renewable hydrogen and to reduce carbon emissions since the ammonia industry uses hydrogen and consumes much energy. ARENA predicts that it can produce 20,000 tons of ammonia using 3,600 tons of renewable hydrogen annually, and it is sufficient to secure 20% of current nitrate demand in Queensland.

ENAEX (explosive manufacturer) and ENGIE (multinational energy company) recently agreed on a strategic alliance to conduct the feasibility study of an ammonia production pilot plant. The project includes the design, construction, and operation of an ammonia production complex based on renewable hydrogen. ENAEX is a major producer of nitrate ammonium, which is a detonator used in the mining industry, in Latin America. It plans to use solar energy that is abundant in the northern Chilean region and expects that it can transform the mining industry to become carbon-free.

In June 2019, Balance Agri-Nutrients (a New Zealand-based fertilizer manufacturer) disclosed its plan to invest USD 50 million for a project in the Kapuni Plant to produce hydrogen and ammonia using renewable energy. The project is scheduled to be completed in 2021. It will produce hydrogen using four wind turbines with a total capacity of 16MW and reduce carbon emissions from the Kapuni Plant by about 2%.

3 Republic of Korea

The Korea Institute of Energy Research (KIER) developed a vehicle that used an ammonia-gasoline mixture fuel in 2013 and disclosed that the engine could operate stably when the ratio of ammonia in the mixture was 70%. It also developed a mixed engine controller that controls ammonia and gasoline independently to generate the optimal mixing rate according to the operating condition, ammonia fuel supply pump, fuel line, and ammonia emission reduction device.

Daewoo Shipbuilding and Marine Engineering (DSME) conducted a technical and commercial feasibility study of ships using ammonia fuel and analyzed the competitiveness of GHG reduction of ammonia fuel compared to HFO (+scrubber) and LNG[8]. The study analyzed the competitiveness and deduced CAPEX and OPEX according to the ship type, fuel price, navigation route, fuel storage method, and tank material. The study result showed that ammonia lowers the production cost and can be sufficiently competitive if the IMO's emission regulation becomes stricter in the future. DSME disclosed that it could develop the ammonia engineering technologies, such as the ammonia supply system and ammonia liquefaction system, and planned to build a cooperation network with other companies related to ammonia fueled ships.

III / Characteristics of Ammonia

The strength of ammonia is that it is relatively easy to store due to the rational energy density (12.7 GJ/m^3) and liquefaction temperature (-33.6℃) compared to hydrogen, the production and transport costs are lower compared to other carbon-neutral fuels, and has the technology for stable production and transport. Although the weakness of ammonia is its toxicity, it has been handled as the liquefied gas cargo, refrigerant of the chiller, and reducing agent of selective catalytic reduction (SCR) in ships for decades. Therefore, handling of ammonia fuel in ships should be sufficiently feasible. This document reviewed the feasibility of ammonia as the future fuel for ships by analyzing the characteristics, economic efficiency, supply stability, and risk of ammonia storage and transport.

1 Ease of Storage and Transpor

The carbon-neutral fuel which is the most advantageous from the storage and transport perspective is biodiesel. Since it has almost the same energy density as existing fossil fuel and can be stored at ambient temperature and pressure, it can use the same fuel system and storage tank as existing ships.

The main component of biogas is methane, which has almost the same properties as LNG. Although the liquefaction temperature is relatively low at –161.6°C, the advancement in the LNG storage tank and fuel supply system has made it possible to be used in ships. Although it requires about 2.3 times larger fuel tank due to the low energy density and the insulation requirement compared to existing fossil fuels, the optimal design that optimizes the fuel tank layout in ships is gradually overcoming the difficulty.

Hydrogen has the highest mass energy density, but its volumetric energy density is very low. The BOG generation is large, because of the low storage temperature of –252.8°C. Therefore thicker insulator is required, and the size of fuel storage tanks is about 7.6 times that of existing fossil fuels. Moreover, the fuel temperature must be raised when supplying the fuel to the engine or fuel cell, and it complicates the fuel supply system configuration. Because of such characteristics, hydrogen is likely to be used only in coastal operating vessels rather than in ocean going vessels.

Methanol has less than half the volume energy density compared to conventional fossil fuels but can be stored at ambient temperature and pressure. Therefore, the size of its storage tank is relatively small compared to other carbon-neutral fuels (about 2.3 times compared to conventional fossil fuels). Methanol fuel can also be used with existing fuel supply systems and fuel storage tanks without major changes.

Liquefied ammonia has a relatively low volume energy density and requires about 4.1 times a large tank compared to conventional fossil fuels. As such, it is necessary to consider freight loss. Although it must be stored in a compression tank or low-temperature tank, the compression tank requires about 10 bar, and the low-temperature tank requires -33.6ºC. Therefore, the design and manufacturing of storage tanks for liquefied ammonia are relatively simple. Ammonia is disadvantageous to biodiesel and methanol from the storage and transport perspective but has superior storage characteristics than biogas and hydrogen.

[Table 1] Storage Characteristics of Fuels to Ships

Fuel	Mass Energy Density LHV(MJ/kg)	Volume Energy Density LHV(GJ/m^3)	Storage Pressure(Bar)	Storage Temperature(ºC)	Relative Tank Size (With Insulator)
MGO	42.8	36.6	1	20	1
Biodiesel	42.2	33.0	1	20	1
Biogas (Liquefied Methane)	55.6	25.0	1	–161.6↓	2.3
Methanol	19.9	15.8	1	20	2.3
Liquefied ammonia	18.6	12.7	1	–33.6↓	4.1
			10	24.9↓	
Liquefied hydrogen	120.0	8.5	1	–252.8↓	7.6

2 Economic Efficiency of Ammonia Fuel

It is very difficult to predict the price of carbon-neutral fuel since biodiesel, biogas, hydrogen, methanol, and ammonia have not been supplied in large quantities as ship fuel, and the fuel status can change sensitively according to the development of related technologies and supply and demand of fuel. Unlike fossil fuels, which use mined energy sources, carbon-neutral fuels are produced for use. Therefore, this document intends to compare the economic efficiency of each fuel by considering the fuel production process.

Biodiesel has a food security problem since it can conflict with food supply as the fuel is produced with crops and marine algae as raw materials. Therefore, it is not widely used across the shipping industry and is expected to be used on a limited basis despite its advantage of being available to current ships without any major modification.

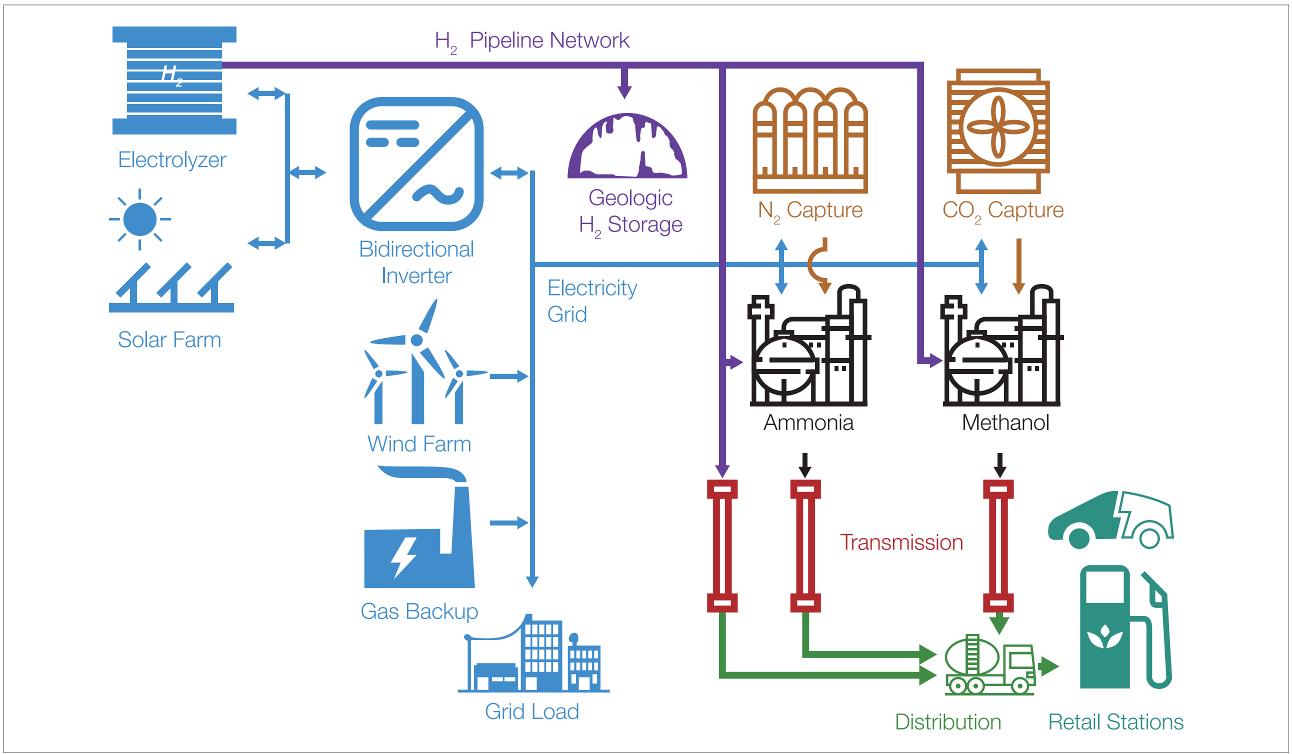
Biogas has the advantage where it can be used in LNG-fueled ships since it is mostly composed of methane gas. However, livestock manure, food waste, and agricultural/fishery waste that are raw materials of biogas are wastes generated by other industries, and it is difficult to increase raw material production just to produce biogas. The following figure shows the production process of hydrogen, ammonia, and methanol fuel.

Hydrogen	Water Electrolysis → Liquefaction → Transport
Ammonia	Hydrogen production (Water Electrolysis) + Nitrogen production → Ammonia synthesis → Liquefaction
Methanol	Hydrogen Production (Water Electrolysis) + carbon dioxide capture → Methanol synthesis

Hydrogen has the advantage that it can be produced immediately by water electrolysis using renewable energy, it must be liquefied at -252.8ºC for large-scale storage after production and thus consumes large energy during the storage and transport process. Hydrogen liquefaction requires about 30% of heat generation[10], and the energy loss increases even more due to BOG generated during the storage and transport process.

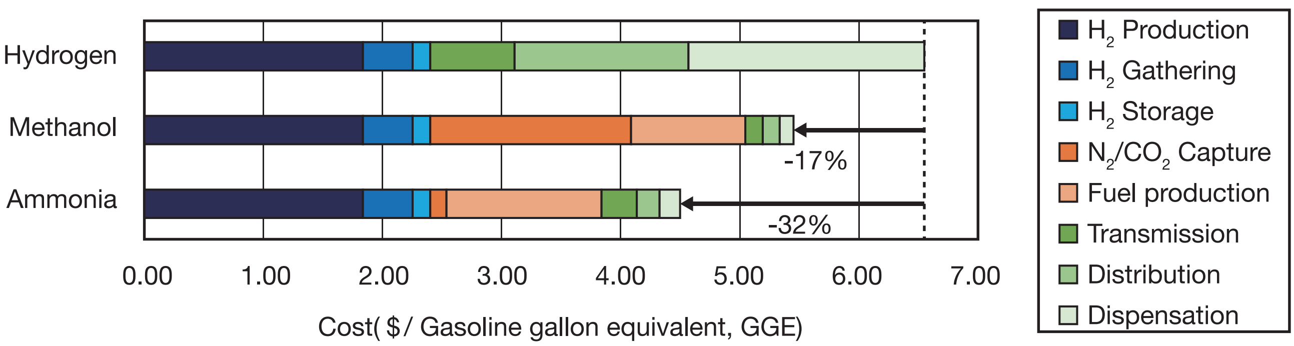
Ammonia and methanol require nitrogen or carbon dioxide, in addition to hydrogen, for synthesis. Although it is possible to produce hydrogen through water electrolysis, a separate process is required to produce nitrogen and carbon dioxide. Nitrogen is required for ammonia synthesis and accounts for about 70% of air. Therefore, it can be easily produced by cryogenic air separation. carbon dioxide is required for the methanol synthesis and, like nitrogen, can be separated from the air. However, its composition in the air is small (~0.04%), and its separation requires much energy. Although it is possible to produce carbon dioxide more easily by capturing it from flue gas of power plants or industrial plants (carbon dioxide concentration of about 12%[11]), it is not desirable from the carbon-neutrality viewpoint since it requires a fossil fuel-based energy source.

Lastly, it is possible to synthesize ammonia and methanol by synthesizing hydrogen and nitrogen and also hydrogen and carbon dioxide. GHG emissions during the production process can be minimized by using renewable energy for synthesis. The following figure shows the process of producing carbon-neutral fuel. One can consider ammonia and methanol also to be a type of hydrogen energy, and it implies that the transport type of the produced hydrogen for use is the key issue.



[Figure 3] Production of Carbon-Neutral Fuel[12]

Figure 4 shows the total energy cost when including the production and transport of each fuel. Hydrogen requires excessive costs for transport, and methanol requires excessive cost for capturing carbon dioxide needed for production. However, the figure confirms that ammonia is a rational fuel when considering the entire production and transport processes, even though the fuel production process is relatively costly



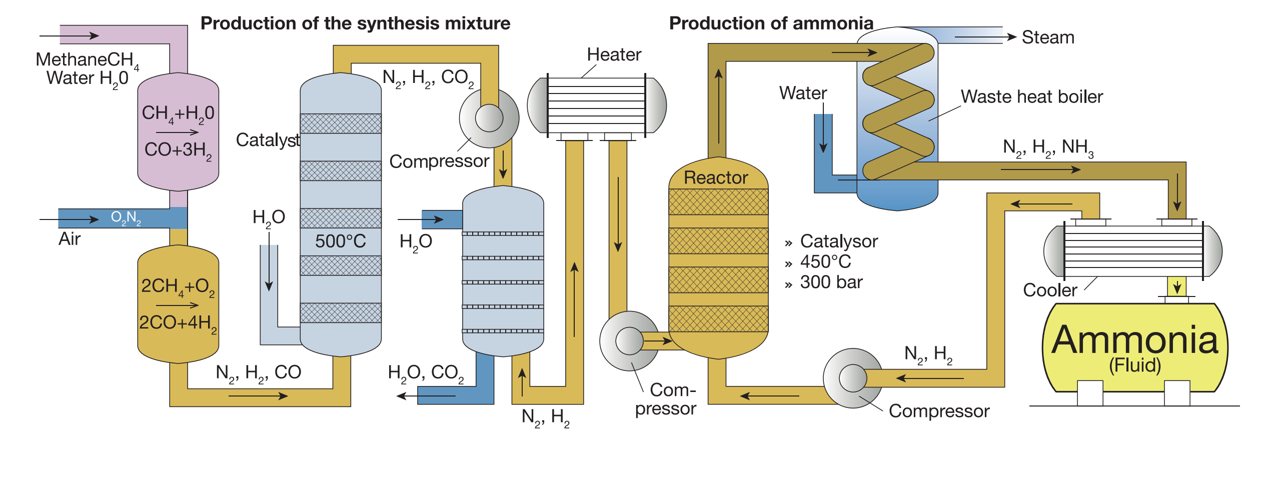
* Hydrogen is the case of compressed hydrogen supply, and the cost is high because of the energy consumption for increasing the pressure to 700 bar or higher.

* The carbon dioxide separation process for methanol production is assumed to be the direct air capture. It is possible to lower the cost when separating carbon dioxide from flue gas, but the case cannot be considered as complete carbon-neutral fuel since it uses fossil fuel to produce carbon dioxide.

[Figure 4] Cost Composition of Carbon-Neutral Fuel[12]

3 Production of Ammonia Fuel

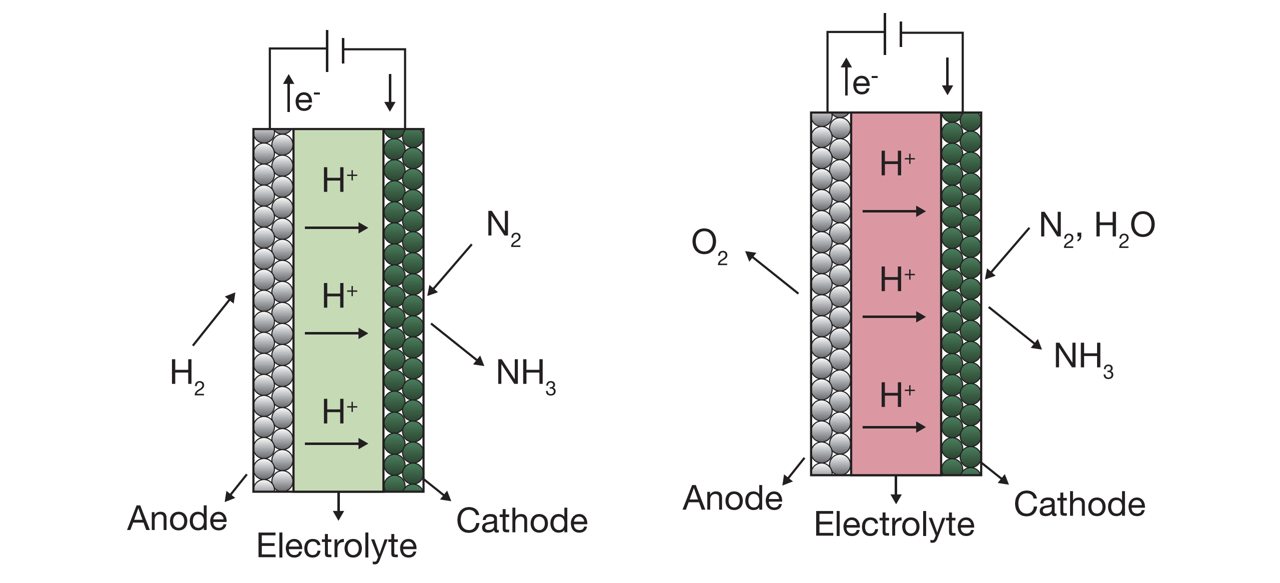
Most of the ammonia is currently used as the raw material for fertilizers. About 180 million tons of ammonia are produced worldwide, and about 10% of them are transported by sea. The Haber-Bosch process, developed in 1918, is still most widely used for ammonia production, since it is the most economical and suitable for mass production. The process reacts hydrogen and nitrogen with a catalyst at high pressure (200-400 bar) and high temperature (450°C)[13]. Hydrogen is extracted by reforming natural gas, and nitrogen is produced by cryogenic air separation.



[Figure 5] Schematic Diagram of the Haber-Bosch Process

Although the Haber-Bosch process consumes a substantial amount of energy since it requires high pressure and high temperature to produce ammonia, many techniques of increasing the process efficiency have been developed, and the efficiency of industrial ammonia synthesis is relatively high at about 70%[14]. In addition, there are many studies on how to produce ammonia electrochemically to improve ammonia synthesis efficiency. As shown in Figure 6, it can reduce the energy consumed by synthesis since it synthesizes ammonia by reacting water and nitrogen electrochemically at atmospheric pressure and low temperature (〈100℃). It can supply the carbon-neutral ammonia in the future since it can produce ammonia directly using renewable energy.

Ammonia has mostly been produced by the Haber-Bosch process until now, and the electrochemical technique has a shortage of commercial reference cases. Therefore, it is expected that the Haber-Bosch process will be used to produce carbon-neutral ammonia in the near future, and carbon dioxide emissions should be reduced by producing the hydrogen needed for the process with renewable energy and Water Electrolysis or natural gas reforming using carbon capture and storage (CCS).



[Figure 6] Schematic Diagram of solid-state electrochemical ammonia synthesis device[15]

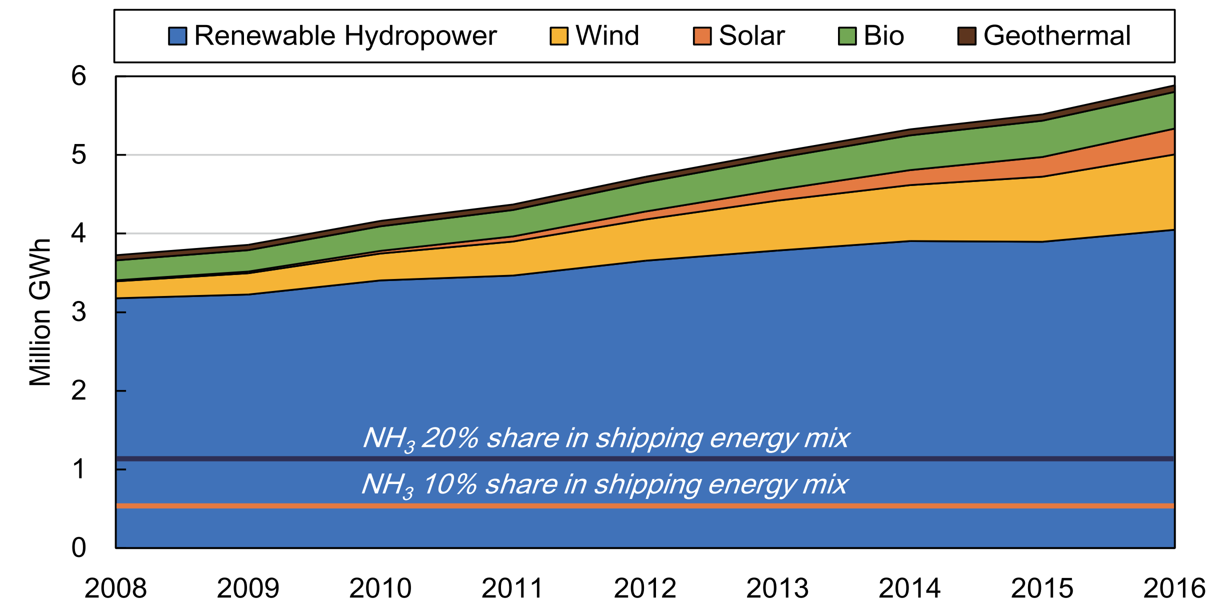
4 Stability of Ammonia Fuel Supply

Since it is technically and commercially feasible to mass-produce ammonia using the Haber-Bosch process, the supply stability of carbon-neutral ammonia in the future depends on how to supply the raw materials, hydrogen and nitrogen, and the process energy using the renewable energy. Therefore, this section analyzes the supply feasibility of carbon-neutral ammonia in the future by comparing the energy currently used by the shipping industry and the power generation from renewable energy.

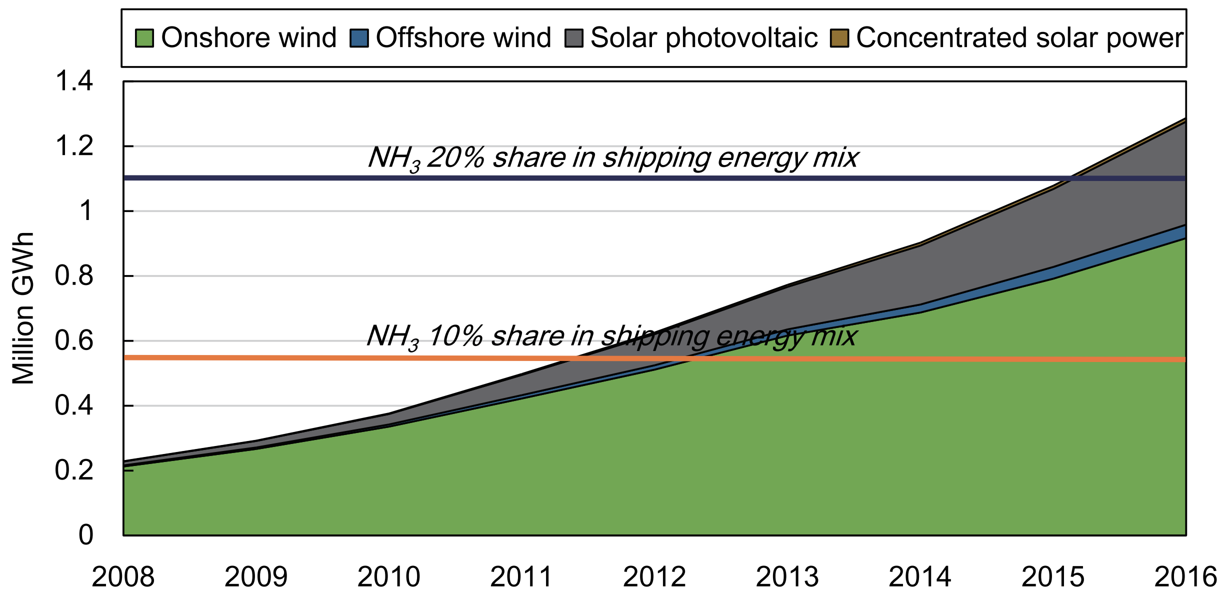
About 3.05 million GWh was used by the international shipping in 2015[16], and substituting about 10% of the consumed energy with carbon-neutral ammonia fuel requires renewal energy of about 550,000 GWh. (The calculation considers the energy required only for ammonia production and not for storage and transport.)

As of 2016, the total power generation worldwide from renewable energy accounted for by hydro, wind, bio, and solar energy in that order was about 5.88 million GWh[19]. Since it is possible to produce about 320,000 GWh ammonia using 10% of renewable energy worldwide, it is feasible to supply about 10% of renewable energy required by international shipping with ammonia. Renewable energy is growing about 6% annually, and the solar and wind power generations are particularly growing fast with the growth rates of 31.3% and 15.8%, respectively, in 2016.

Moreover, in order to meet the IMO's GHG reduction target, the amount of energy consumed by international shipping needs to decrease after peaking in 2030 approximately. Therefore, the total amount of energy consumed by international shipping is not expected to grow significantly in the future. On the contrary, the power generation from renewable energy is increasing every year, so it is expected that supplying ammonia fuel to some of the international shipping vessels would be sufficiently feasible.



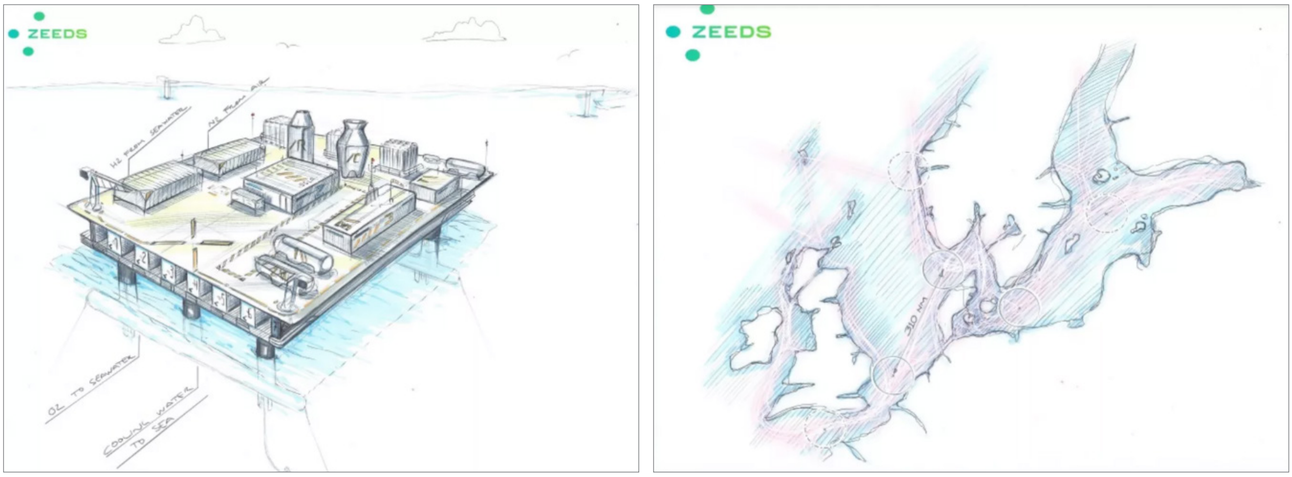
(a) Power generation by renewable energy



(b) Solar and wind energy status

[Figure 7] Power Generation from Renewable Energy[17]

Interest in offshore solar power generation and wind power generation has grown significantly in order to secure sites for solar and wind power plants and efficient power generation. In that case, it is possible to reduce the cost of transportation and storage by producing the hydrogen and ammonia at ports using the power generated at sea and supplying them directly to ships. Wärtsilä proposed the concept of installing wind turbines to produce ammonia at ports and supplying the fuel to ships (Figure 8)[6].



[Figure 8] Schematic Diagram of ZEEDS (Zero Emission Energy Distribution at Sea)[5]

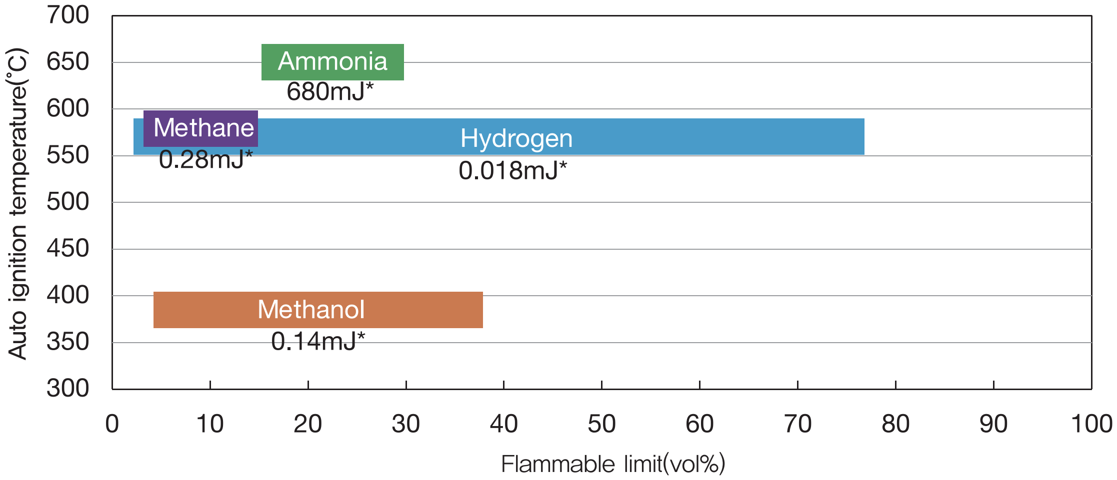
Considering the increasing trend of power generation with renewable energy and the synergy of offshore solar and wind power generation with the supply of fuel to ships, the supply of ammonia fuel to ships is sufficiently feasible, and its economic efficiency is expected to be high enough as the carbon regulations in shipping become strict. Moreover, a method of producing hydrogen cost-effectively and environmentally friendly using carbon capture and storage (CCS) during the reforming of natural gas is being discussed. There are also research and development of the technique of producing ammonia electrochemically. As such, the production and supply of ammonia as the carbon-neutral fuel would become more feasible.

5 Risk of Ammonia Fuel

Ammonia is a flammable gas, but the lower flammability limit is high, and its flammable range is not wide. The spontaneous ignition temperature is high at 651°C compared to other fuels, and the minimum ignition energy of 680 mJ is more than 2,000 times higher than methane. Since ammonia is basically a flammable gas, like other gas fuels, its ignition source must be isolated. However, the risk of fire is low compared to other fuels since the flammability limit is small, and the conditions for ignition (spontaneous ignition temperature and minimum ignition energy) are difficult.

The most dangerous property of ammonia is its toxicity. Therefore, using ammonia fuel requires a suitable sensing system, additional safety system (ventilation, water spray to dissolve ammonia, etc.), and response manual.

As shown in Tables 2 and 3, ammonia can be fatally toxic to humans, depending on the concentration and exposure time. Although it induces a slight irritation even after a prolonged exposure if the concentration is 30 ppm or lower, even a relatively short exposure at the concentration of about 220 ppm can cause severe damage, and a long exposure at the concentration of 390 ppm or higher can cause fatal damage. However, due to its unique smell, ammonia can be easily detected at a lower concentration of 1.5 ppm, much lower than 30 ppm that can harm the human body.



*MIE(Minimum Ignition Energy)

[Figure 9] Flammable limit of Fuels[18,19]

[Table 2] Hazard to Human Body According to Ammonia Concentration

5	Concentration(ppm)	Unique detectable smell
6-20	Concentration(ppm)	Eye irritation and problems to the respiratory system
40-200	Concentration(ppm)	Headache, nausea, loss of appetite, and irritation of airway, nose, and throat
400	Concentration(ppm)	Irritation of throat
700	Concentration(ppm)	Eye damage
1700	Concentration(ppm)	Coughing and difficulty of breathing
2500-4500	Concentration(ppm)	Fatal damage
5000	Concentration(ppm)	Possible death due to respiratory arrest

[Table 3] Criticality According to Ammonia Concentration and Exposure Time[20]

(unit : ppm)

Type	10 min	30 min	60 min	240 min	480 min
AEGL 1	30	30	30	30	30
AEGL 2	220	220	160	110	110
AEGL 3	2,700	1,600	1,100	550	390

*Acute Exposure Guideline Levels (AEGL): Ammonia
- AEGL 1 : Causes irritation but is recoverable immediately when the exposure is stopped
- AEGL 2 : Causes irreversible or long-lasting health hazards
- AEGL 3 : Fatal

Ammonia has been handled as the liquefied gas cargo, refrigerant of the chiller, and reducing agent of selective catalytic reduction (SCR) in ships, and there are regulations for safe handling of ammonia. A gas transport ship built according to the IGC Code (International Code of the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk) can transport ammonia. Ammonia has a high possibility of causing the stability problem of ship structure and human casualties when leaked due to its corrosive and toxic properties. The IGC Code requires the minimum conditions, as shown in Table 4, to cope with such problems.

[Table 4] Minimum Requirement of Ammonia in the IGC Code

Ship type	Independent tank type C required	Control of Vapor space within cargo tanks	Vapor detection	Gauging	Special Requirements
2G/2PG	-	-	Toxic vapour detection	Indirect, or Closed	14.4.2 14.4.3 14.4.4 17.2.1 17.13

- 14.4.2 Safety Equipment
- 14.4.3 First Aid Equipment
- 14.4.4 Personal protection requirements for individual
- 17.2.1 Material of structure: Mercury, copper, and copper-bearing alloy. Zinc should not be used for cargo tank, pipe, valve, or attachment.
- 17.13 Special requirements of ammonia: Ammonia can cause stress corrosion fracture in carbon-manganese steel or nickel steel, and measures to minimize the risk is needed.

In addition to ship cargo, ammonia is used as the refrigerant for chiller, and “Section 4 Special Requirements for Refrigerating Machinery Using Ammonia as Refrigerant of Part 9 Additional Installations” in Rules for the Classification of Steel Ships by the Korean Register specifies the regulation to handle ammonia safely. According to the regulation, devices to remove ammonia gas at the time of ammonia leakage include ventilation system, gas absorption system, water curtain system, and gas-absorbing water tank. Since ammonia is easily soluble in water to up to 45% at the freezing point, water can be used to effectively remove ammonia at the time of ammonia leakage. The following safety and protective devices are required for easy access in case of ammonia leakage.

① Protective clothing (helmet, safety boots, gloves, etc.) x 2
② Self-contained breathing apparatus (capable of functioning for at least 30 minutes) x 2
③ Protective goggles x 2
④ Eye washer x 1
⑤ Boric acid
⑥ Emergency electric torch x 2
⑦ Electrical Insulation Resistance Meter x 1

[Table 5] Gas Removal Device(Special Requirements for Refrigerating Machinery Using Ammonia as Refrigerant, Korean Register)

Ventilation system	• Installation of a mechanical ventilation system capable of 30 air changes per hour • Ventilation fan of non-sparking type is to be provided
Gas absorption system	• Installation of scrubber or water sprinkler system • When the gas concentration in the refrigerating machinery compartment exceeds 300 ppm, the pump is to start automatically
Water screening system	• All doors of the refrigerating machinery compartment are to be provided with water screening system
Gas absorption water tank	• Installed at a position lower than the refrigerating machinery compartment so that the leaked liquid ammonia can be recovered quickly • The tank is to have such a capacity that the water which can absorb the refrigerant filled in at least one refrigerating machinery can be fully recovered • Overflow from the tank is to be diluted or neutralized and then discharged overboard directly, without leading the discharge pipes through accommodation spaces

Ammonia can be used as a reducing agent of the SCR system for reducing nitrogen oxides, and “Section 1 Selective Catalytic Reduction system Using Ammonia Solutions or Urea Solutions as the reducing agents(SCR)” of Guidance for Exhaust gas Emission Abatement System specifies the use. The Guidelines describe the ammonia storage tank, structure and arrangement of solution spray system, material ventilator, pipes, drain tank, ventilator, gas detection and alarm system, and safety and protective gear. Although the specification is similar to “Section 4 Special Requirements for Refrigerating Machinery Using Ammonia as Refrigerant of Part 9 Additional Installations” in Rules for the Classification of Steel Ships by the Korean Register in most cases, it does not require the gas absorption system, water screening system, and gas absorption water tank.

Since the IGC Code currently prohibits using toxic cargo (ammonia, etc.) as fuel, it is not possible to use ammonia as a fuel for ships. Moreover, ships using natural gas as fuel must be built according to the IGF Code (International Code of Safety for Ships Using Gases or Other Low-Flashpoint Fuels), and there are also discussions about fuels other than natural gas. However, the discussions of using ammonia fuel have not yet begun.

This section has described the handling of the ammonia in ammonia carrier, chiller, and selective catalytic reduction and confirms that there are rules and methods to handle ammonia safely inside ships. Ammonia has been transported in bulk by liquefied gas carriers built according to the IGC Code, and it is also possible to safely handle ammonia used as a refrigerant in the freezer unit and the catalyst reducer in the exhaust gas emission-reducing device in ships. Therefore, using ammonia as a fuel for ships is expected to be sufficiently feasible through the revision of the IGF Code and IGC Code.

6 Ammonia as the Medium for Transport of Hydrogen

Despite the difficulties of storing and transporting hydrogen due to its low energy density and cryogenic liquefaction temperature, which is difficult to store and transport, there is a strong interest in a decarbonized hydrogen society around the world. It has been proven that marine transport is the most efficient way to transport large quantities of energy sources, such as crude oil and LNG, economically over long distances, and hydrogen is also expected to be transported by ships.

The Korean Government announced the Roadmap for Promotion of Hydrogen Society in January 2019 with the goal of realizing the hydrogen society that includes the production, storage, transport, and utilization of hydrogen used throughout the society. Although it is possible to produce hydrogen using renewable energy, it is necessary to import it from other countries by ship transport to fulfill the domestic demand.

The storage methods to transport hydrogen with ships include compressed hydrogen, liquefied hydrogen, liquid-phase organic compound (LOHC), and ammonia. Compressed hydrogen is not suitable for marine transport since it has the lowest energy density, and it is difficult to manufacture large, high-pressure tanks. Although liquefied hydrogen, unlike LOHC and ammonia, has the advantage of not requiring the additional separation process after transport, hydrogen must be liquefied at about -252.8°C, consuming an excessive amount of energy, and there is a problem of hydrogen loss due to evaporation during the transport. Moreover, high-priced tanks are needed for cryogenic storage, and additional infrastructure is also needed for cryogenic hydrogen. LOHC can be stored and transported at room temperature and atmospheric pressure but requires a dehydrogenation process to utilize hydrogen, and it consumes much energy. On the other hand, ammonia has the highest hydrogen storage density per unit volume and is easy to liquefy. Moreover, as mentioned above, it has been used for fertilizer production for a long time, and there is are ready production processes and transport infrastructure. It can also be used immediately by combustion without having to be decomposed into hydrogen. Therefore, it can be an advantageous hydrogen transporting medium in many aspects.

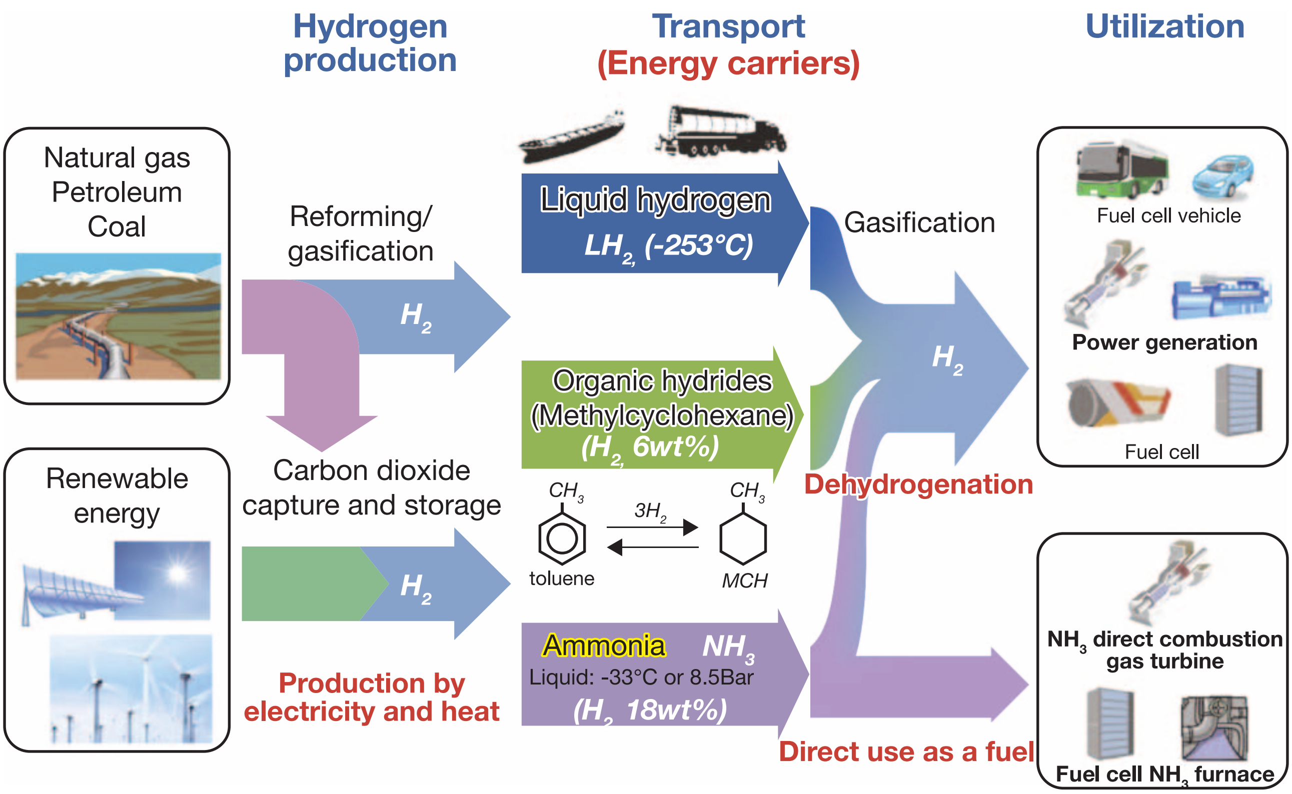
This is why ammonia has gained attention as the key hydrogen transporting medium, and Japan regards ammonia as the key element for realizing the hydrogen society, as shown in Figure 10.

The production, transport, and utilization of ammonia as the hydrogen transport medium are likely to increase, and the ammonia industry is expected to grow along with the hydrogen industry as the hydrogen economy is established worldwide. Such growth of the ammonia industry will lead to the economy of scale and lower the production and transportation cost and increase the competitiveness of ammonia fuel even more.

[Table 6] Characteristics of Hydrogen Transport Mediums[21]

Type	Liquefied hydrogen (LH_2)	Liquid-phase organic compound (LOHC)	Ammonia (NH_3)
H_2 contents (wt%)	100	6.2	17.8
Volumetric hydrogen density (kg–H_2/m^3)	70.8	47.3	121
H_2 release enthalpy change (KJ/mol–H_2)	0.9	55 - 71	30.6
Hydrogenation, synthesis, and liquefaction energy efficiency	Low	High	High
Hydrogenation (dehydrogenation), synthesis (decomposition), and liquefaction (gasification) speeds	High	Low	Low
Hydrogen generation pressure (Pressure for gasification, dehydrogenation, and decomposition)	Low	High	Moderate
Toxicity	None	Moderate	High
Transport and facility cost (Vehicle, storage container, ship, etc.)	High	Low	Low
Flammability limit (vol.%)	4 - 74	1.2 - 6.7	15 - 28

*Methylcyclohexane (MCH) basis ($CH_3C_6H_{11}$) in the case of LOHC



[Figure 10] Schematic Diagram of Hydrogen Value Chain Including Ammonia[22]

7 Ammonia Fuel-Powered Engine & Fuel Cell

Because of its poor fuel properties (flash point, minimum ignition energy, flame speed, etc.), it is difficult for conventional engines to use pure ammonia. The studies to supplement these characteristics have focused on mixing ammonia with other fuels to enhance the combustion properties of the fuel rather than improving engine technologies (such as strengthening ignition plug and increasing compression ratio). The spark ignition uses the mixture with hydrogen and gasoline, while the compression ignition mostly uses the mixture with diesel. MAN Energy Solutions[3] disclosed that more than 3,000 existing MAN B&W engines can be modified into ammonia fuel engines and that ammonia fuel-driven ships can be realized by future R&D and engine retrofit.

In the case of fuel cells, ammonia cannot be used directly and must be reformed into hydrogen to be used in low-temperature fuel cells like PEMFC but can be used as-is for fuel in high-temperature fuel cells (SOFC). However, most studies have focused on the development and commercialization of fuel cells using hydrogen as fuel more than fuel cells that use ammonia.

[Table 7] Combustion Properties of Fuel

Fuel	Minimum Ignition Energy(mJ)	Spontaneous Combustion Temperature(ºC)	Octane Value	High Flame Speed(m/s)
Ammonia	680	650	111	0.09
Hydrogen	0.018	520	130	2.91
Methane	0.28	630	120	0.37
Methanol	0.14	385	106	0.50
Diesel	20	210	25	

Spark Ignition (SI) Engine

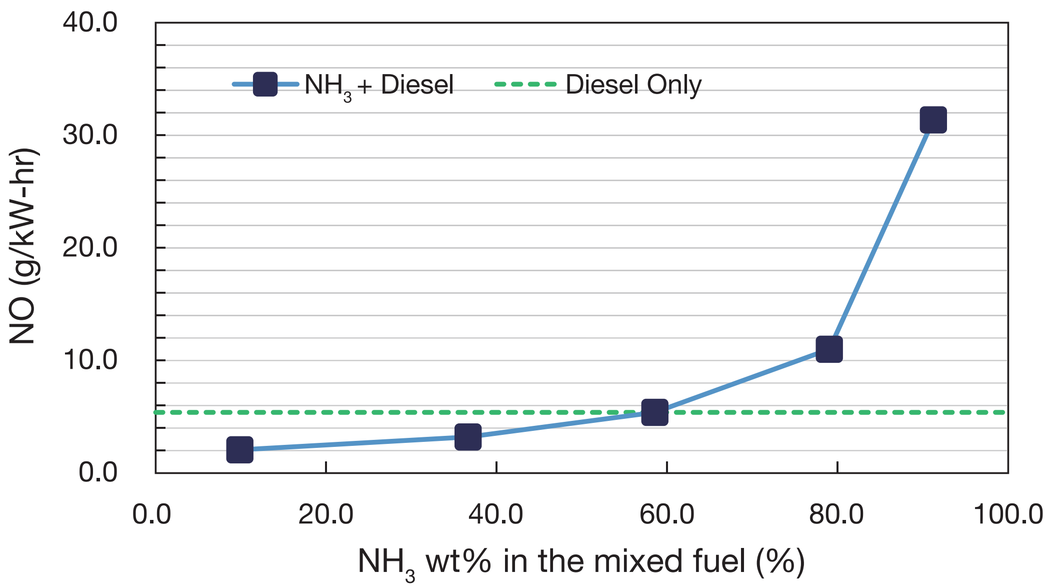
The minimum ignition energy of ammonia is 680mJ (more than 2000 times the methane) or higher, and the octane number is about 110. Therefore, it is necessary to use an ignition plug with high ignition energy or multiple ignition plugs. Even with combustion, it is very difficult to completely combust ammonia inside the combustion chamber due to the low flame speed (about 4 times slower than methane). Therefore, studies on the ammonia SI engine uses a mixture with other fuels (mostly hydrogen) to supplement the combustion properties. The method, like conventional SI engines, injects the mixture gas of ammonia and other fuels into the combustion chamber through the intake valves and burning the fuel using the ignition plugs. The ratio of hydrogen in the ammonia-hydrogen mixture for stable combustion is known to be about 5 wt%.

Compression Ignition (CI) Engine

When using pure ammonia as a fuel, the combustion of ammonia is known to be possible at the compression ratio of 35:1 due to the high spontaneous combustion temperature (650℃). It is much higher than the typical CI engine that requires 16 - 23:1, indicating that it would be difficult to design and manufacture the CI engine using ammonia as fuel.

Therefore, studies have focused on CI engines using the mixture with other fuels, such as diesel dimethyl ether, dimethylhydrazine, and kerosene, as was the case for SI engines. There were many studies of CI engine using the ammonia-diesel mixture as fuel, and they reported that the optimal ratio of diesel was 20 - 40wt%[24, 25]. Most studies injected ammonia gas into the combustion chamber through intake valves and directly injected diesel fuel as a pilot fuel to burn the fuel. The stable combustion is possible at the compression ratio of 20:1 or lower, much lower than that needed by pure ammonia.

For CI engines, it is necessary to check the generation of nitrogen oxide since much nitrogen oxide is generated due to the high temperature and pressure inside the combustion chamber and the nitrogen content in ammonia. The studies have reported that the generation of nitrogen oxide differed according to the mixing rate of ammonia and diesel. The amount of nitrogen oxide generation increases greatly when the ratio of ammonia increases. The generation of nitrogen oxide decreases more when the ratio of ammonia is less than 60% due to the lower flash point than when pure diesel fuel is used but increases rapidly due to the nitrogen content in the ammonia fuel as when the ratio of ammonia increases. The generation of nitrous oxide (N_20), in particular, can increase greatly[26], and it is a strong GHG with the Global Warming Potential that is about 300 times that of carbon dioxide. Therefore, it should be noted that using ammonia as fuel can partially offset carbon dioxide emission reduction. However, there is a shortage of R&D on the post-processing system of exhaust gas of the ammonia engine. As such, the research and development of the post-processing system of exhaust gas of ammonia engine for ships with consideration to different nitrogen oxide generation mechanisms according to the ammonia-diesel mixing ratio, high sulfur content (possibility of generation of ammonium bisulfate (ABS)) of ship fuel compared to ground fuel, and unburned ammonia.



[Figure 11] Exhaust NO Emissions under Constant Power Output Operation using various Ammonia-Diesel Ratio[23]

Polymer Electrolyte Membrane Fuel Cell (PEMFC)

The PEMFC uses the polymer member that can permeate hydrogen ions as the electrolyte. It is widely used in fuel cell electric vehicles for its fast ignition and response characteristics. Since it uses hydrogen as fuel, the ammonia must be reformed before it is used as fuel for ships. The PEMFC is a low-temperature fuel cell and thus cannot use waste heat, the overall energy efficiency is greatly lowered due to additional fuel consumption for ammonia reforming. Therefore, it is more logical to use it with SOFC and mutually supplement the weakness of each fuel cell for the application to ammonia ships.

Solid Oxide Fuel Cell (SOFC)

SOFC uses solid oxides that can permeate oxygen or hydrogen ions as the electrolyte. It operates at the highest temperature (about 1,000℃) among the existing fuel cells. Unlike PEMFC, the high-temperature fuel cell can use ammonia as fuel, and all components are in the solid phase. Therefore, the structure is simple, and there is no problem with electrolyte loss and supplementation or corrosion. Moreover, unlike internal combustion engines, it has the advantage of requiring no exhaust gas processing system since no fine dust nor nitrogen oxide is generated.

It has been mostly studied for land power generation and is generally known to be unsuitable for transportation because of poor response characteristics. Therefore, SOFC would be more effective as a power generator engine rather than a driving engine for the near future. In the future, it would be possible to replace the internal combustion engine for propulsion with the hybrid system that supplements the weakness of SOFC by using the fuel cell and the battery/PEMFC.

IV Conclusion

1 Ammonia as Carbon Neutral Marine Fuel

There is no fuel that is superior to any other fuels in every aspect, and each fuel has advantages and disadvantages. There is no doubt that hydrogen, one of the carbon-neutral fuels for ships, is a green fuel of the future, but it requires some time because of technical difficulties and low commercial value compared to other fuels. Ammonia has relatively low technical and is produced with hydrogen as fuel. As such, it should be considered as another medium to store hydrogen energy and can be the eco-friendly fuel for ships that can be used with hydrogen fuel by supplementing the disadvantage of hydrogen in the future hydrogen society.

① Biodiesel and biogas are the carbon-neutral fuel that is almost the same as existing fossil fuels and thus can be used most easily. However, it is unstable from the fuel supply perspective and thus can be used in a mixture with other fossil fuels.

② Hydrogen is the carbon-neutral fuel with low a product production cost, but its storage and transport cost is very high due to the low energy density and cryogenic liquefaction temperature, and the fuel tank must be large, leading to the increased shipbuilding cost.

③ Methanol has the advantage of storage at room temperature and atmospheric pressure but requires carbon dioxide for synthesis and energy for carbon dioxide capture, resulting in costly fuel production.

④ Ammonia is expected to have low production, storage, and transport costs compared to other carbon-neutral fuels, and the stable fuel supply is possible as the large-capacity ammonia synthesis technologies are already mature. It can be regarded as the carbon-neutral fuel for ships with the growth potential since it is expected to be at the allowable level technically and commercially from the storage temperature, energy density, and shipbuilding cost perspective.

Each fuel for ships has advantages and disadvantages, and fossil fuels and carbon-neutral fuels are in mutually supplementary relations. It is possible to compensate for GHG emissions by fossil fuels by purchasing carbon credits or by using carbon-neutral fuels for dual-fuel engines. Carbon-neutral fuel may be used only for short-range operation, and fossil fuels may be used in dual-fuel engines if it is difficult to reduce the size of fuel tank or supply of carbon-neutral fuel is not feasible. Therefore, diversification of fuels for ships is essential in the future shipping market, and shipping companies would have to select fuel in consideration of the fuel price, supply-demand status, navigational route, and regulation.

[Table 8] Strength and Weakness of Fuels

Type	MGO	LNG	Bio gas	Bio diesel	Methanol	Ammonia	Hydrogen
Fuel type	Fossil fuel		Carbon-neutral fuel				
Storage condition	Ambient temperature and pressure	-161.6℃	-161.6℃	Ambient temperature and pressure	Ambient temperature and pressure	-33.6℃ or 10bar	-252.8℃
Relative Fuel Tank size[27]	1	2.3	2.3	1	2.3	4.1	7.6
Relative CAPEX	1	~1.3	~1.3	1	~1.15	~1.2	Very expensive
Fuel cost & Availability	Less expensive and rich reserves		Difficult to mass produce due to the fuel sourcing problem	Difficult to forecast the price due to unstable supply and demand and the food security problem	High cost of CO_2 capture* (when capturing CO_2 from air)	Expensive but relatively low priced for carbon-neutral fuel	Reasonable fuel production cost but high storage and transport costs

*Although it is possible to lower the cost by capturing carbon dioxide from combustion gas (exhaust gas from power plants), it is not the carbon–neutral fuel since it uses carbon dioxide produced by fossil fuel.

Excellent Acceptable Undesirable

2 Forecasting of Ammonia Fuel Engine and Fuel Cell

Although fuel cells offer very high efficiency and eco-friendliness as the propulsion system for future ships, they are not likely to be applied to ocean operating ships in the near future. Hydrogen fuel cells are expected to be applicable to near sea operating ships and small ships since the infrastructure industry related to ships using fuel ships is not yet mature. Ammonia is a pre-hydrogen fuel that is considered to be rationally applicable to ships in the near future based on the mature internal combustion technology. As the LNG fuel driving technology developed from the LNG transport ships led to LNG fuel-driven ships, ammonia freight can be used as fuel for ammonia transport ships initially, and then the use of ammonia fuel is expected to be expanded to other ship types.

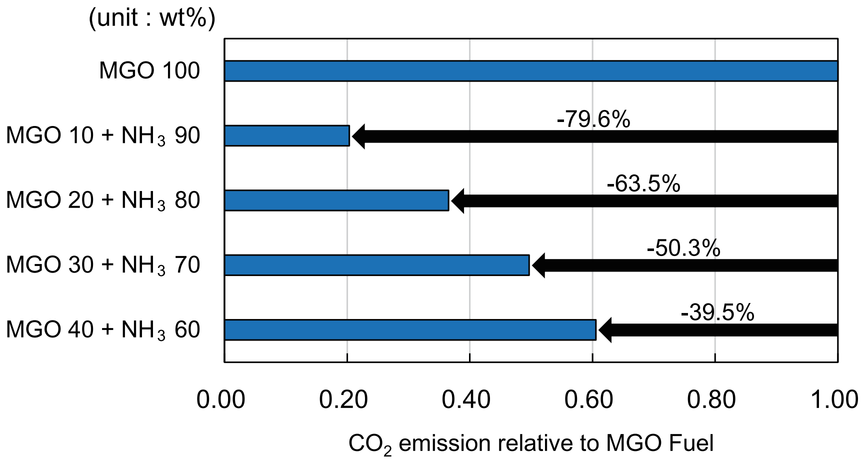
① The spark ignition engine, which uses the mixture of ammonia with hydrogen and gasoline, is likely to be used in small ships since it is difficult to increase the capacity.

② The compression ignition engine, which uses diesel oil as the ignition source, is suitable for large ships, and it is expected that the engine can be developed by modifying the two-stroke ammonia-diesel dual-fuel engine, which is widely used in large ships. Since the current two-stroke engines for large ships have a relatively high efficiency of about 50% and are very mature technically and commercially, it would be easy to develop the ammonia engine based on the current engine.

③ Ammonia-diesel dual-fuel engines can use both ammonia and fossil fuel. As such, the shipping companies can select fuel flexibly while meeting the regulation. It is possible to lower carbon dioxide emissions by about 40% when using the mixture fuel of the existing fuel MGO and ammonia (NH_3) in the ratio of 4:6 compared to using only MGO, and reduction can be as high as 80% if the mixture ratio is 1:9. It would be possible to comply with the ever-stricter GHG regulation by applying low-speed operation, operation optimization, ship type optimization, waste heat recovery (WHR), and carbon credit purchase while using fossil fuel and ammonia together as fuel to ships. Therefore, ammonia-diesel dual-fuel engines would become very popular during the transient period of switching from fossil fuel to carbon-neutral fuel for ships.

④ Moreover, it enables stable ship operation while meeting the GHG emission regulation since it can use fossil fuel if the supply of ammonia fuel is difficult.

⑤ However, there is an issue with nitrogen oxide generation caused by the nitrogen content in the ammonia fuel, and it requires further studies.



[Figure 12] Carbon Dioxide Emission by MGO-Ammonia Mixture Fuel Compared to MGO Fuel

Since PEMFC, which is widely being developed for transport currently, requires ammonia reforming for use, using the hybrid driving engine that uses SOFC with PEMFC or battery or replacing the power generator engine with SOFC is more suitable. It should be noted that the fuel cell for ships is not yet technically and commercially mature, and fuel cells can be used for the driving system of small or near sea operating ships or for power generation in large ocean operating ships. The increase in the application for fuel cell electric vehicles on ground and the fuel cell power plant capacity should lead to cost reduction from technology stability and mass production. It is likely to lead to the applicability of fuel cell driving systems in ships

Category	Sub Category	Fuel	Efficiency	Strength	Weakness
Internal combustion engine	Compression ignition (CI	Ammonia	~50%	» Engine operation without using another fuel or reforming ammonia	» A relatively high compression ratio of 35:1 needed (compared to the conventional diesel compression ratio of 23:1) » Attention to unburned ammonia and nitrogen oxide discharge
		Ammonia + diesel	~50%	» Retrofit of existing internal combustion engine » Flexible use of fossil fuel according to the ammonia fuel supply status (Operational security)	» Discharge of CO_2 since fossil fuel is used also » Attention to unburned ammonia and nitrogen oxide discharge
	Spark Ignition (SI)	Ammonia	~50%	» Engine operation without using another fuel or reforming ammonia » Less nitrogen oxide generation than CI engines	» Difficult to ignite ammonia » Poor combustion efficiency due to the combustion properties of ammonia » Not suitable for large ships
		Ammonia + hydrogen	~50%	» Combustion properties similar to methane obtained when mixing hydrogen with ammonia » No need to bunker hydrogen additional since it can be obtained by reforming ammonia	» Reformer to reform ammonia » Not suitable for large ships
Fuel cell	PEMFC	Hydrogen	50 ~ 60%	» Low-temperature fuel cell with quick ignition and excellent response characteristics » Excellent efficiency even at low loads » No discharge of air pollutants	» Efficiency decrease due to the need for the reformer, purifier, and burner » Lack of technical and commercial maturity
	SOFC	Ammonia	60 ~ 65%	» Use of ammonia as a fuel » High-temperature fuel cell to be able to use waste heat » No discharge of air pollutants	» Long ignition time and poor response characteristics » Lack of technical and commercial maturity

[Figure 13] Strengths and Weaknesses of Internal Combustion Engines and Fuel Cells

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