Chapter 2

Utilisation of Ammonia for Decarbonisation

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Chapter 2

Utilisation of Ammonia for Decarbonisation

1. World Ammonia Market

Ammonia is an internationally traded commodity and has an established global market. As a primary feedstock for urea and fertiliser, ammonia has a global supply chain from upstream production to the pipeline, maritime loading infrastructure, tankers, unloading infrastructure, storage tanks, and downstream processing units to convert ammonia into final products. It has also established commercial practices such as supply contracts and pricing schemes. Since ammonia's quality as a fuel is the same as ammonia as a chemical product, the existing infrastructure can be utilised as a supply chain for ammonia as fuel without significant modification. A global market infrastructure greatly helps lower the initial hurdle of adopting ammonia as a fuel for power generation.

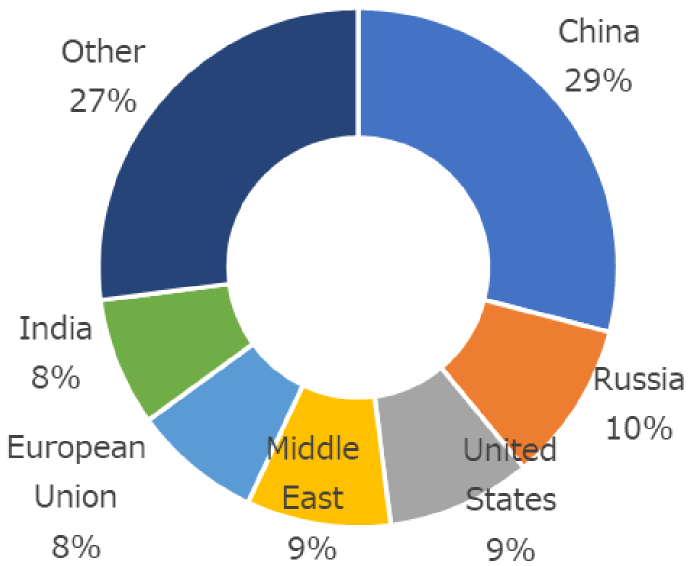
The global ammonia production as of 2019 was approximately 180 million tonnes per year. The volume is indeed one of the largest amongst various chemical products. Ammonia has a large production volume because it is a major fertiliser feedstock. Approximately 80% of the world's ammonia production is processed into urea and then into chemical fertiliser. Because fertiliser is critical for the agriculture sector, its demand also exists in almost every corner of the world. Besides as a fertiliser feedstock, the remaining 20% of the global ammonia production is utilised as various chemical products. Ammonia can be used as a feedstock of plastic, melamine resin, synthetic fiber (nylon), and synthetic rubber. It can also be used as an absorbent of nitrogen oxide (Nox), a pollutant emitted from the combustion of fossil fuels, such as coal and petroleum products.

Most of the world's ammonia is produced from a well-known chemical process named Haber-Bosch process, named after German scientists who found and established the production of ammonia from nitrogen and hydrogen. This innovative process significantly expanded the supply of ammonia and fertiliser that uses ammonia as feedstock. Most of the world's ammonia production facilities are integrated into urea and fertiliser production facilities.

Hence, most ammonia is locally produced and consumed.

While ammonia production facilities exist globally, almost half the global production capacities exist in Asia, particularly in East Asia (Figure 2.1). China is the largest ammonia producer worldwide, and its share of production capacity is approximately 30% as of 2019 (IEA, 2021b). The second-largest supply region is Eurasia, where Russia is a core producer. Thanks to its vast natural gas reserves, Russia can produce hydrogen, an ammonia feedstock, at a competitive cost. Backed by such cost competitiveness, Russia is the largest ammonia exporter globally. Likewise, the Middle East is another major ammonia production and export region. For many Asian countries, the Middle East is a primary ammonia exporter because of its relative geographical proximity and large production capacity.

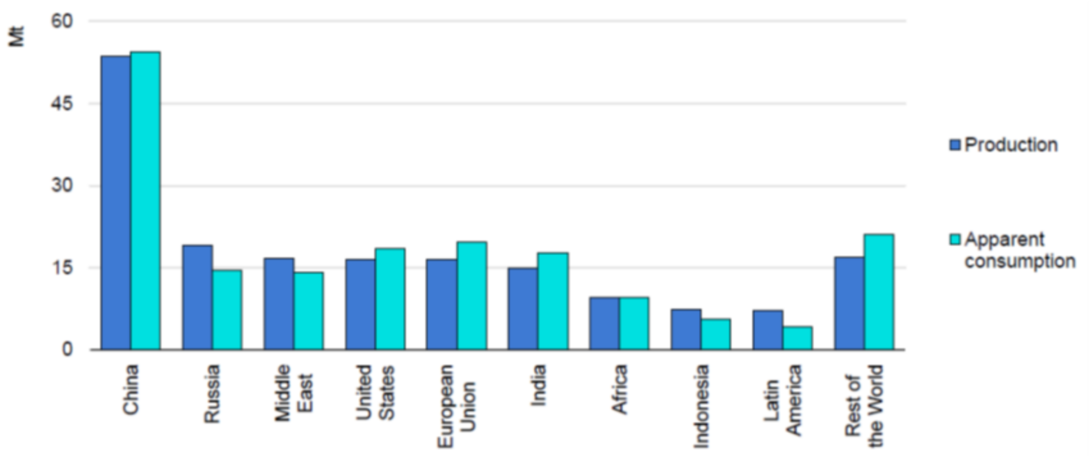
Figure 2.1. World Ammonia Production



Source: IEA (2021b, p. 23)

The geographical distribution of ammonia demand is similar to that of production (Figure 2.2). Most ammonia production capacities are integrated into urea and fertiliser production facilities. Only a limited capacity is devoted to ammonia production without its downstream processing units. Region-wise, China is by far the largest demand location, followed by the Europe Union and the United States (US), where the population is large, and so is the feedstock demand for fertiliser. India, which has 1.3 billion people with growing income and food consumption, has increased its fertiliser and ammonia demand in recent years.

Figure 2.2 World Ammonia Supply and Demand



Source: IEA (2021c, p. 24).

The traded volume of ammonia is approximately only 10% of the world's total production. This is because, as noted above, most ammonia production is integrated into urea and fertiliser production. The largest exporter of ammonia as of 2019 was Russia, followed by Trinidad and Tobago. Middle Eastern countries also significantly contribute to supplying ammonia to the international market. On the other hand, major ammonia importers comprise developed countries, most notably the European Union and the US. India, which has a large population but lacks competitive natural gas feedstock, is also a major importer of ammonia. Russia has been known as a stable exporter of ammonia until today. Because of the war in Ukraine and related economic sanctions on Russia, uncertainties have grown about Russia's exports as of the writing of this report in April 2022.

2.2. Fuel Use of Ammonia

Ammonia's physical properties

The ammonia molecule is represented by the chemical formula NH_3, composed of nitrogen and hydrogen atoms, and is a colourless gas at room temperature and pressure. In 1906, German scientists Fritz Haber and Karl Bosch developed the Haber-Bosch process, a technique for artificially synthesising ammonia from hydrogen and nitrogen in the air. This enabled humankind to produce useful nitrogen-containing compounds, such as nitrogen fertilisers and explosives.

As of 2021, the major use of ammonia includes chemical fertilisers, raw materials for chemical products such as synthetic fibres and explosives, and as an agent to reduce nitrogen oxides (Nox) in the exhaust from thermal power plants to harmless nitrogen and water vapour. Current global production is approximately 180 million tonnes/year, about 80% of which is used for chemical fertilisers. Ammonia is an international commodity whose price is determined by the market, and a global supply chain has already been established. About 10% of the total world production is traded internationally.

Ammonia reacts with oxygen and decomposes into nitrogen and water (steam) based on the following chemical reaction formula, $2NH_3 + 1.5\ O_2 \rightarrow N_2 + 3H_2\ O$. Because of this property, ammonia can be used as fuel like natural gas or petroleum.

Here the authors compare the physical properties of ammonia with methane, the main component of natural gas, which is also a gaseous fuel and still widely used today, and hydrogen, which like ammonia is expected to become popular as a non-carbon fuel.

Table 2.1. Comparison of Ammonia, Methane, and Hydrogen

Physical Properties	Ammonia	Methane	Hydrogen
Condition at room temperature and pressure	gas	gas	gas
Molecular weight	17.030	16.041	2.016
Boiling point (under ambient pressure)	-33°C	-162°C	-253°C
Volumetric energy density (HHV) MJ/Nm^3	17.0	39.8	12.8
Gravimetric energy density (HHV) MJ/kg	22.0	55.5	142.0

Density (gas) kg/m^3	0.771 (standard condition)	0.717 (standard condition)	0.090 (standard condition)
Density (liquid) kg/m^3	603.0 (25°C, 10 atm)	442.5 (-162°C, saturated state)	70.8 (-253°C, saturated state)
Liquefaction by compression at room temperature	Yes (20°C, 8.46 atm)	No (Critical temp.: -82°C)	No (Critical temp.: -253°C)
Toxicity	Toxic, corrosive	None, but may cause asphyxiation if inhaled in large quantities	None, but may cause asphyxiation if inhaled in large quantities
Combustion speed (air combustion) m/s	0.08～0.09	0.37～0.40	2.91
Combustible concentration (mixing rate with air, % by volume)	15.5~27	5~15	4~75
Ignition point (°C)	651	580	572

Source: IEEJ's compilation based on publicly available information.

All three fuels are liquefied for transport by containers. But while methane and hydrogen must be kept at extremely low temperatures to liquefy, ammonia liquefies by compression at ambient temperature. Ammonia is a non-carbon fuel that is relatively easy to transport.

Regarding combustion characteristics, ammonia's flame speed is only one-fourth of methane during air combustion. It also has a higher ignition point than hydrogen or methane. Because of these properties, ammonia is a fuel difficult to ignite and burn stably.

Almost all fuels produce nitrogen oxides (Nox), which are air pollutants, by oxidising nitrogen in the air during combustion. In addition, ammonia requires special consideration for combustion because its molecules contain nitrogen, which can also be a source of Nox.

Because of its high toxicity and the need for qualified personnel to control it as a toxic substance, under Japanese law, it is not likely to be used for consumer purposes like other hydrocarbon fuels, such as city gas and liquified propane gas.

Fuel use of ammonia

Examples of ammonia fuel use include its use as an alternative fuel for transit buses during World War II and the flight of US experimental aircraft with liquid ammonia-fueled rocket engines in the 1950s and 1960s.

As of 2021, the use of ammonia as fuel was considered a countermeasure to tackle climate change. Two types of ammonia combustion methods are considered: mixed combustion, in which ammonia is mixed with other fuels, and dedicated combustion, in which ammonia is the only fuel, and the choice depends on the application and scale.

Gas turbine combustion

A combustion property of ammonia, difficult to burn, will require larger combustors when used in gas turbines. Therefore, large gas turbines that use multiple combustors in a single turbine may require major design changes from gas turbines that use natural gas. In ammonia co-firing in gas turbines, it has been pointed out that a phenomenon known as combustion oscillation may occur due to significant changes in the properties of the fuel, and countermeasures are needed. The generation of Nox from fuel components, which does not occur when natural gas is used as fuel, also requires countermeasures. In addition, ammonia combustion produces nitrous oxide N_2O, which has a greenhouse effect 298 times greater than CO_2. At present, there is no N_2O decomposition catalyst, so it is necessary to establish a combustion technology that can control N_2O production. The following summarises the technological trends in ammonia combustion in gas turbines when this report was written.

Operation with 100% ammonia had been achieved in a small gas turbine with 50 kW power output.[24] This operation reached a Nox concentration of 25 ppm after passing through the Nox reduction catalyst, compared to a Nox concentration of 164 ppm at the turbine outlet.

A gas turbine with 300 kW power output operates at rated power with a fuel composition of 82.4% ammonia and 17.6% methane and achieves a Nox concentration of 2 ppm after passing through a Nox reduction catalyst. When the turbine was operated with 89.7% ammonia and 10.3% methane, the power output dropped to 261 kW, and the Nox concentration after passing through the catalyst increased to 43 ppm.

Mitsubishi Power announced that it is developing a 40 MW class ammonia-dedicated combustion gas turbine for power generation.[25] For large gas turbines in the several hundred MW class, ammonia could be decomposed, and fuel gas, consisting of hydrogen and a small amount of ammonia, could be burned in a hydrogen-fired gas turbine.[26,27] This method is said to allow the use of ammonia from existing gas turbines with minimal modifications required.

Combustion in burners and boilers

The first fuel use of ammonia in boilers for thermal power generation is co-firing with coal (discussed in detail in section 4).

Specific research and development of 100% ammonia-fired boilers for power generation do not appear to have been conducted due to concerns about the generation of N_2O mentioned above and the fact that gas turbine–combined cycles are more efficient in burning liquid and gaseous fuels.

[24] Toyota Energy Solutions Inc., SIP (Strategic Innovation Program), Subject name 'Energy Carrier', Research and Development Theme, 'Ammonia Direct Combustion', Research Title: 'Ammonia Combustion Micro Gas Turbine', Completion Report, 2019, 3 (in Japanese).

[25] Nikkei XTECH/Nikkei Electronics, 40 MW class ammonia dedicated-fired thermal power generation, Mitsubishi Power to launch in 2025, Nikkei XTECH, 2021.03.02, https://xtech.nikkei.com/atcl/nxt/news/18/09771/ (accessed January 2021) (in Japanese).

[26] Mitsubishi Hitachi Power Systems Corporation, SIP (Strategic Innovation Program), Subject name 'Energy Carrier', Research and Development Theme 'Ammonia Direct Combustion', Research Title 'Technical Development of Ammonia Utilisation Gas Turbine (System and Combustor)', Completion Report, 2019, 3 (in Japanese).

[27] Mitsubishi Heavy Industries Engineering Corporation, SIP (Strategic Innovation Program), Subject name 'Energy Carrier', Research and Development Theme 'Ammonia Direct Combustion', Research Title 'Technical Development of Ammonia Utilisation Gas Turbine (Examination of Ammonia Decomposition Equipment)', Completion Report, 2019, 3 (in Japanese).

Ammonia is also envisioned for use in industrial burners.[28] The studied applications include industrial furnaces for steel plate degreasing[29] and cement firing furnaces.[30]

Combustion in reciprocating engines

In ammonia combustion in spark-ignition reciprocating engines, co-combustion with methane and dedicated combustion have been studied.[31] Results show that reciprocating engines can be operated using existing combustion control technology. However, it is difficult to change the power output, and fixed-point operation at a high load is required. On the other hand, the combustion efficiency is lower than methane combustion, and further analysis of basic combustion phenomena is required.

2.3. Outlook of Fuel Ammonia Production

As earlier noted, today's major ammonia producers are China, Eurasia, and the Middle East. But as fuel demand gains extensive attention, several projects to construct a new ammonia production capacity have been announced in various parts of the world. Amongst them, the Middle East has the largest planned capacities. Saudi Arabia, for instance, is set to become the largest fuel ammonia exporter in the near future. Saudi Aramco, the country's state-owned oil company, plans to develop specific natural gas fields in Saudi Arabia's eastern province exclusively for 'blue' ammonia production combined with carbon capture and storage arrangements (Davis, 2021). The production capacity may be expanded to as large as 10 million tonnes per year. Saudi Arabia also pursues another ammonia production project based on 'green' hydrogen, which is produced from water electrolysis by renewable energy. The Haber-Bosch process converts hydrogen from renewable energy into fuel. NEOM, the country's giant project to develop a world-class hub of renewable energy in the country's

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[28] Taiyo Nippon Sanso Corporation, SIP (Strategic Innovation Program) Subject name 'Energy Carrier', Research and Development Theme 'Direct Ammonia Combustion', Research title 'Technical Development of Ammonia Combustion Furnace Completion Report, 2019, 3 (in Japanese).

[29] Nisshin Steel Corporation, SIP (Strategic Innovation Program), Subject name 'Energy Carrier', Research and Development Theme 'Direct Combustion of Ammonia', Research title 'Technical Development of Ammonia Mixed Combustion Impingement Jet Flow Degreasing Furnace', Completion Report, 2019, 3 (in Japanese).

[30] Ube Industries, Ltd, SIP (Strategic Innovation Program), Subject name 'Energy Carrier', Research and Development Theme 'Direct Combustion of Ammonia', Research title 'Technological Development of Ammonia-Mixed Cement Kiln', Completion Report, 2019, 3 (in Japanese).

[31] Toyota Central R&D Labs Corporation, SIP (Strategic Innovation Program), Subject name 'Energy Carrier', Research and Development Theme 'Ammonia Direct Combustion', Research title 'Development of Combustion Technology for Ammonia Reciprocating Engine', Completion Report, 2019, 3 (in Japanese).

western region, plans to produce and export such green ammonia. NEOM, along with ACWA Power and Air Products as joint venture partners, plans to produce 1.2 million tonnes of green ammonia annually (Darasha, 2021).

Abu Dhabi of the United Arab Emirates also plans to build a new blue ammonia plant for export. The production capacity is much smaller than that of Saudi Arabia at 1 million tonnes per year. A unique aspect of this blue ammonia project is that it will be integrated with enhanced oil recovery (EOR), which captures CO_2 to increase crude oil production. Unlike CCS, which injects and stores CO_2 underground, EOR can generate profits by realising improved crude oil production efficiency. Because the production entity can expect additional revenues from EOR by increasing crude oil production, the project owner can expect higher revenues and profit (ADNOC, 2021).

Australia hosts numerous fuel ammonia projects of both green and blue hydrogen. As for the blue ammonia, Woodside, an Australian oil and gas major, plans to produce blue ammonia in Western Australia utilising natural gas feedstock. Their initial production capacity is 1,500 tonnes per day (Matsumoto, 2021), but the capacity will likely be expanded depending on the development of final demand in Asia. Mitsui & Co, a Japanese trading house, also plans to develop another fuel ammonia project with support from the state-owned Japan Oil, Gas, and Metals National Corporation (JOGMEC, 2021). In addition to such blue ammonia projects are more than 10 green ammonia projects.[32] Some of them are planned on Tasmania Island, which has favourable wind power generation conditions. Australia also has good solar power generation resources, and such renewable energy is planned to be used as a source of green ammonia production.

The US may not be considered a major fuel ammonia exporter. However, given its abundant natural gas resources with CCS and EOR capacities, it is well-positioned to be a significant blue ammonia producer. Also, it has great onshore wind energy resources that can be utilised to produce green hydrogen and ammonia. Mitsubishi Corporation, a Japanese trading house, is currently exploring the potential to commercialise blue ammonia production and export projects in the Gulf of Mexico region (Mitsubishi Corporation, 2021). Furthermore, because the US has a federal tax credit system for domestic CCS and EOR projects, a blue ammonia production and export project may benefit from such a preferred taxation system.

[32] Authors' count based on publicly available media sources.

Latin America, most notably Chile, is known for its competitive renewable energy resources. One preferred location for wind power generation is in the southern end of the South American continent (Patagonia region), where the capacity factor exceeds 60% (IEA, 2021c). Taking advantage of these very competitive renewable energy resources, Chile plans to reinvent itself from an importer of hydrocarbon energy resources to an exporter of green hydrogen and its derivative products, including green ammonia.

In addition to the above export projects, several plans to build fuel ammonia plants were pursued in Russia, one in Siberia, and the other in the Yamal Peninsula. But as the war in Ukraine rages and the US, the European Union, and other countries have imposed economic sanctions on Russia, prospects of such fuel ammonia project have become increasingly invisible.

2.4. Potential (Future) and Challenges of Ammonia Co-firing in Thermal Power Generation (Coal Fired)

Coal-fired power plants are a type of steam-powered power plant in which high-temperature, high-pressure steam produced by a boiler is blown into a turbine, which rotates to generate electricity by turning a generator. Unlike gas turbines used in natural gas–fired power plants, the gas produced by combustion does not directly contact the turbine. Usually, coal is fed to the boiler after it has been crushed into small pieces. Therefore, ammonia in liquid or gaseous form is supplied to the boiler by mixing with air for combustion.

Since coal-fired power generation has higher carbon content in its fuel than natural gas, replacing a portion of the coal with a non-carbon fuel significantly reduces CO_2 emissions intensity. Ammonia is considered a non-carbon fuel for this mixing. The fact that thermal power plants have facilities that handle ammonia for denitrification (removal of nitrogen oxides) of exhaust gas is one of the reasons ammonia is being considered for use. The co-firing ratio is generally 20% on a calorific value basis. A Japanese power generation company, JERA's Hekinan Thermal Power Plant, is planning to conduct a 2-month power generation demonstration test using 20% ammonia mixed with coal, the main fuel, in FY2024.[33]

The CO_2 emission reduction effect of this 20% ammonia co-combustion with coal is about 1 million tonnes per year for a 1,000 MW class power plant. If this were done at all coal-fired

[33] https://www.jera.co.jp/english/information/20210524_677.

power plants in Japan, annual CO_2 emissions would be reduced by 40 million tonnes, or approximately 10% of Japan's 400 million tonnes/year of CO_2 emissions, from the power generation sector.

Japan's domestic demand for ammonia is said to be about 1 million tonnes per year. If a 1,000 MW coal-fired power plant were to co-fire ammonia at 20% of its calorific value, annual ammonia consumption would be approximately 500,000 tonnes. If all coal-fired power plants in Japan were to co-fire 20% ammonia, annual ammonia consumption would reach 20 million tonnes. As seen above, even a 20% coal–ammonia co-firing system, if implemented on a large scale, would require far more ammonia in the power generation sector than the current total demand for ammonia in Japan. Procuring this at a low cost and in a stable manner will be a challenge for the practical application of coal–ammonia co-firing. In addition, for this technology to contribute to the decarbonisation of society, the life cycle CO_2 emissions of the ammonia used must be reduced, and the integration of technologies for making ammonia from hydrogen derived from renewable energy sources and CCS into the production of ammonia from fossil fuels is needed.

2.5. Cost Analysis of Coal–Ammonia Mixed Combustion

Assumptions

In general, ammonia price is higher than coal's, so ammonia co-firing in coal-fired power plants increases the cost of power generation. Here, we will conduct a quantitative evaluation to determine the extent to which ammonia co-firing increases the cost of power generation.

Under the assumption that coal-fired power plants are operated in Japan, we calculate the approximate economics of ammonia co-firing in coal-fired power plants. Two types of co-firing ratios are assumed here: 20% and 50% on a calorific value basis. Therefore, the authors set the following three cases for this analysis:

- BAU case: Normal coal-fired power plant
- Ammonia-20 case: Co-firing of 20% ammonia on a calorific value basis in a coal-fired power plant in the BAU case
- Ammonia-50 case: Co-firing of 50% ammonia on a calorific value basis in a coal-fired power plant in the BAU case

This study uses the levelised cost of electricity (LCOE) as a cost index. This index is based on the study of the Power Generation Cost Verification Working Group of the Agency for Natural Resources and Energy, Japan,[34] which is regarded as a standard for evaluating power generation costs in Japan. This evaluates the cost of power generation for a given operating period and is calculated by dividing the net present value of all costs required within the operating period by the net present value of generated electricity. The unit of measure is the unit cost of electricity generated (e.g. yen (¥)/kWh or US$/kWh).

The exchange rate is assumed to be ¥110/US$. The facility is assumed to operate for 40 years in all three cases. The discount rate for present value conversion is assumed to be 3% per year, and fuel calorific value and efficiency are calculated based on the higher heating value (HHV).

Table 2.2 shows the assumptions regarding capital and operation and maintenance costs. The basic condition settings follow the assumptions of the Power Generation Cost Verification Working Group.[35] Capital costs for ammonia co-firing facilities are based on the assumptions of J-Power Corporation.[35] The ammonia co-firing facility is assumed to be able to co-fire 20% to 50% on a calorific value basis in the same facility.

Table 2.2. Assumptions about Capital and O&M Costs

Item	Value	Unit
Equipment capacity	700	MW
Capacity factor	70	% per year
Internal rate	5.5	%
Power generation efficiency	43.5	% (HHV basis)
Construction cost per unit capacity	24.4	¥10^4/kW
Cost of equipment	1,708	¥10^8

[34] Agency for Natural Resources and Energy, Advisory Committee on Natural Resources and Energy, Power Generation Cost Verification Working Group (8th Meeting) Document 3: List of Specifications of Power Sources, 2021, 9 (in Japanese).

[35] J-Power Corporation, SIP (Strategic Innovation Program), Program Name ‘Energy Carrier,’ Research and Development Theme ‘Development of Ammonia Production, Storage, and Transportation Technologies Using CO_2-Free Hydrogen’, Research Title: ‘Technical Study of CO_2 Free Ammonia Supply Chain as a Fuel for Thermal Power Generation’, Completion Report, 2019, 3 (in Japanese).

Facility decommissioning cost ratio (vs. construction cost)	5	%
Personnel expenses	4.4	¥10^8/year
Repair cost ratio (vs construction cost)	2.4	% per year
Miscellaneous expenses ratio (vs construction cost)	2.2	% per year
General management expenses ratio (vs direct cost)	12.20	% per year
Ammonia co-firing facility cost	278	¥10^8
Ammonia co-firing facility decommissioning cost ratio (vs construction cost)	5	%
Fuel miscellaneous expenses	0.077	Yen/MJ-fuel

HHV = higher heating value, O&M = operation and maintenance.

Sources: Agency for Natural Resources and Energy, Advisory Committee on Natural Resources and Energy, Power Generation Cost Verification Working Group (8th Meeting) Document 3: List of Specifications of Power Sources, 2021, 9 (in Japanese); J-Power Corporation, SIP (Strategic Innovation Program), Program Name 'Energy Carrier,' Research and Development Theme 'Development of Ammonia Production, Storage, and Transportation Technologies Using CO_2-Free Hydrogen', Research Title: 'Technical Study of CO_2 Free Ammonia Supply Chain as a Fuel for Thermal Power Generation', Completion Report, 2019, 3 (in Japanese).

Table 2.3 shows the assumptions about coal. These assumptions refer to the Japanese government's material for generation cost calculation.[36]

[36] Agency for Natural Resources and Energy, Advisory Committee on Natural Resources and Energy, Power Generation Cost Verification Working Group (8th Meeting) Document 3: List of Specifications of Power Sources, 2021, 9 (in Japanese).

Table 2.3. Assumptions about Coal

Item	Value	Unit
Calorific value	26.08	MJ/kg
Price	108.58	$/t
Price per calorific value	0.458	Yen/MJ
CO_2 emission factor	89.1	g-CO_2/MJ

Source: Agency for Natural Resources and Energy, Advisory Committee on Natural Resources and Energy, Power Generation Cost Verification Working Group (8th Meeting) Document 3: List of Specifications of Power Sources, 2021, 9 (in Japanese).

Assumptions regarding ammonia are shown in Table 2.4. These assumptions are based on a study by The Institute of Energy Economics, Japan (IEEJ). The CO_2 emission factor of ammonia is 0, namely, ammonia in this study is so-called blue ammonia or green ammonia.

Table 2.4. Assumptions about Ammonia

Item	Value	Unit
Calorific value	17.0	MJ/Nm^3
Density (gas)	0.77	kg/Nm^3
Price	338.5	$/t-$NH_3$
Price per calorific value	1.69	Yen/MJ
CO_2 emission factor	0	g-CO_2/MJ

Sources: Agency for Natural Resources and Energy, Advisory Committee on Natural Resources and Energy, Power Generation Cost Verification Working Group (8th Meeting) Document 3: List of Specifications of Power Sources, 2021, 9 (in Japanese); J-Power Corporation, SIP (Strategic Innovation Program), Program Name 'Energy Carrier,' Research and Development Theme 'Development of Ammonia Production, Storage, and Transportation Technologies Using CO_2-Free Hydrogen', Research Title: 'Technical Study of CO_2 Free Ammonia Supply Chain as a Fuel for Thermal Power Generation', Completion Report, 2019, 3 (in Japanese).

6. Result

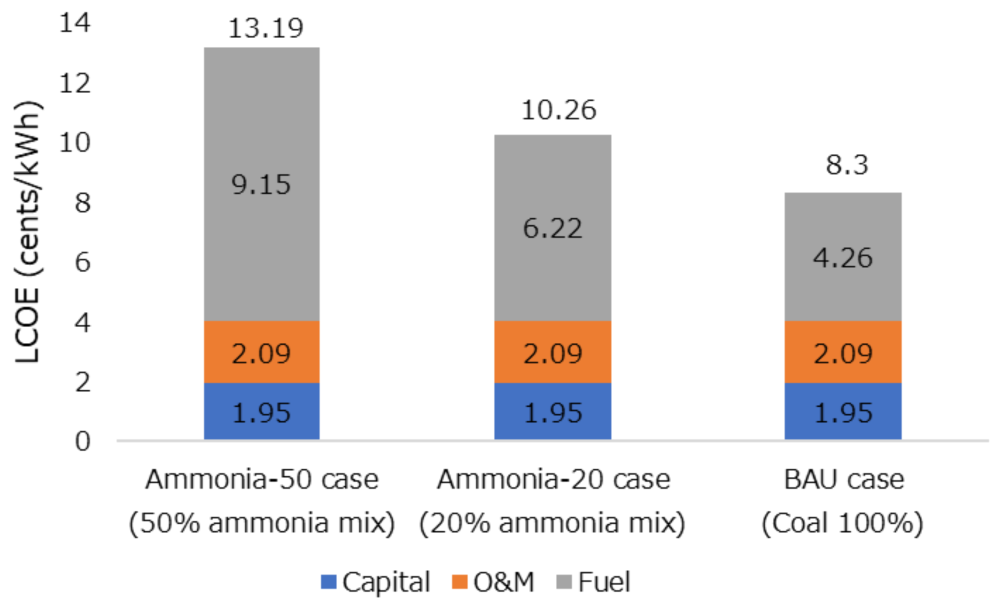
Figure 2.3 shows the calculated LCOE. The LCOE of the Ammoina-20 case is 128% of BAU; that of Ammonia-50 case is 164%. The breakdown shows that this increase is largely due to the increased fuel cost caused by ammonia, which is more expensive than coal.

The present value equivalent investment and generated electricity, the numerator and denominator of the LCOE, are shown in Table 2.5.

Figure 2.4 indicates that CO_2 emissions over 40 years of operation decrease in proportion to the co-firing rate. The original coal-fired power plant emits 127 million tonnes of CO_2 during its 40-year-long operating period. CO_2 emission reduction effects are 26 million tonnes/40 years by 20% mixed combustion and 64 million tonnes/40 years by 50% mixed combustion.

These results indicate that the incremental power generation cost required to reduce CO_2 emissions by 20% and 50% through ammonia co-firing in coal-fired power plants is 2.23 cents/kWh and 5.16 cents/kWh, respectively.

Figure 2.3. Levelised Cost of Electricity



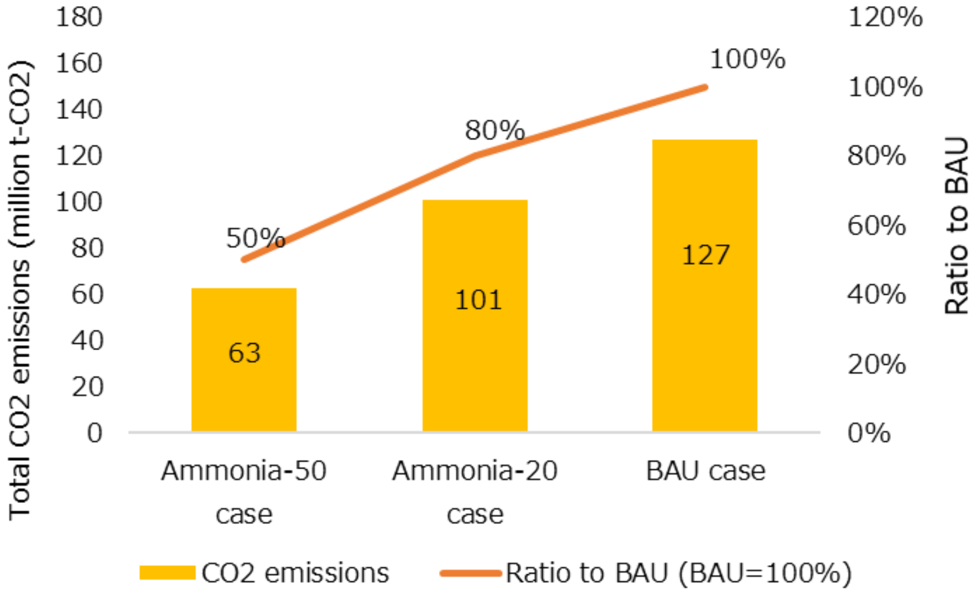
Source: IEEJ's estimate based on Tables 2.2, 2.3, and 2.4.

Table 2.5. Discounted Total Cost and Generated Power

Discounted Total Cost (million US$)	Ammonia-50 Case (50% ammonia - mix)	Ammonia-20 Case (20% ammonia - mix)	BAU Case (100% Coal)
Capital	1,833	1,832	1,576
Coal-fired power station	1,553	1,553	1,553
NH_3 mixer	253	253	0
Demolition	27	26	23
O&M	1,956	1,956	1,956
Fuel	8,579	5,828	3,993
Fuel	8,004	5,253	3,419
Fuel misc.	575	575	575
Total	**12,368**	**9,615**	**7,525**
Discounted generated power (GWh)	93,761	93,761	93,761

Source: IEEJ estimate based on the assumptions of Table 2.2, 2.3, and 2.4.

Figure 2.4 CO_2 Emissions during the 40-year-long Operating Period



Source: IEEJ estimate based on the assumptions of Table 2.2, 2.3, and 2.4.