PRE-FEASIBILITY STUDY ON A GREEN AMMONIA SUPPLY CHAIN FROM CHILE TO JAPAN

The Institute of Energy Economics, Japan

September 2023

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*This report has been written with the support of several private companies.

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EXECUTIVE SUMMARY

The Institute of Energy Economic, Japan

In November 2021, IEEJ(2021) [1] evaluated the economics and GHG emissions of establishing an international supply chain to extract hydrogen from liquefied hydrogen, ammonia, or MCH imported from Australia, Saudi Arabia, the United States, and Chile to Japan. The study revealed that under given conditions, green ammonia produced in northern and southern Chile was highly competitive. Based on the results of this study, an in-depth study was conducted from April 2022 through February 2023 with the cooperation of Japanese private companies, including electric power companies, a shipping company, an engineering company, and a trading company. The cost structure of the green ammonia supply chain from Chile to Japan was further analyzed to evaluate the feasibility of building a green ammonia supply chain and identify policy challenges and solutions.

1. Outline of study

In this study, the most economically optimal ammonia production plant design was simulated based on the assumption that renewable power would primarily be procured through power purchase agreements (PPAs). The variability of these renewable power sources and the demand of the electricity for ammonia plant operation would be balanced/supplied by grid electricity in the north, using energy attribute certificates (EACs) to prove the green attributes of the electric power used, and hydrogen gas turbines in the south. Hourly solar generation profiles in Antofagasta and hourly wind power profiles in southern Chile were considered. As a result, it was concluded that the optimal annual production capacity would be one million tons of ammonia in northern Chile, and 780,000 tons, in southern Chile using an ammonia plant with a nominal capacity of 3,000 ton/d.

1 The Institute of Energy Economics, Japan (2021) “Study on the Economics of the Green Hydrogen InternationalSupply Chain” https://eneken.ieej.or.jp/data/9882.pdf

For the shipping of ammonia, given that main engines fueled by ammonia are still in the development stage, heavy oil-powered VLGCs (very large LPG carriers) were applied. The ammonia was assumed to be discharged at multiple ports for use in different coal-fired power plants (500 MW and 1 GW) operated by two different Japanese electric power companies. It was assumed that 20% ammonia would be co-fired with coal at each power plant.

Using the results of our considerations of the green ammonia production, marine transportation, and utilization phases of the supply chain,we conducted a sensitivity analysis on the unit generation cost based on coal and ammonia prices. The results confirmed the cost competitiveness of Chilean green ammonia and were consistent with IEEJ (2021). It was also shown that green ammonia is less volatile against coal price volatility, compared to blue ammonia which is derived from fossil fuels, including coal. However, whether green ammonia from Chile has an overwhelming competitive advantage over that imported from other countries is subject to diverse uncertainties. Various countries have begun to consider exporting hydrogen and ammonia to Japan, and a competitive environment is expected to be fostered in the future. For Japan, the cheaper the hydrogen and its derivatives, the better; and therefore, it is important to strengthen and ensure the competitive advantage of Chilean green ammonia across the value chain.

Chile's abundant renewable energy potential gives it an advantage in low-cost green hydrogen production, mainly from solar and wind energy sources. Further reductions in renewable energy costs will result in reductions in hydrogen production costs. In addition, green hydrogen derived from renewable energy has a carbon intensity (CI value) of almost zero, making it an important alternative to fossil fuels for achieving carbon neutrality.

In recent years, geopolitical risks are continuing to rise around the world, and preparedness for potential disruptions in global supply chains will greatly affect the business continuity of private companies and ultimately a country's stability. The diversification of resources will contribute to energy resilience in the event of a crisis. Securing an energy procurement network that is not limited to conventional energy exporting regions and countries will contribute to improving Japan's energy security. This is an advantage of importing green hydrogen from Chile.

2. Challenges and proposals for the early development of a green ammonia supply chain from Chile to Japan

The study also revealed the challenges to be addressed and possible solutions for the early realization of projects:

(1) Building the business environment in Chile

Given the high capacity factor and low cost of renewable electricity in Chile, green hydrogen and its derivatives produced in Chile potentially bears world-class price competitiveness, but calls for improvements in the business environment, including institutional support. A demonstration of policy support for the further reduction of grid power costs and for the development of common infrastructure (transmission lines, port facilities, etc.), as well as subsidies, tax incentives, deregulation, and procedural streamlining, including clarifying and accelerating the procedures and guidelines for acquiring environmental permits and approvals and developing one-stop project approval procedures, would be reassuring to project developers and investors considering long-term projects in Chile.

(2) Long-term procurement of low-carbon grid power

Large-scale renewable energy projects require long lead times before they can be operational. Therefore, an urgent challenge would be building a system that allows grid electricity with a low carbon footprint to be used for hydrogen production for the early establishment of hydrogen production projects. However, Chile's current grid capacity is not sufficient to supply power to multiple large-scale hydrogen projects. Effective measures include not only reinforcing transmission lines, but also effectively using currently curtailed electric power through charge surplus power during the day for discharge during the nighttime, as well as promoting the employment of water electrolyzers to provide grid flexibility. Furthermore, there is an urgent call for an internationally-recognized nationwide tracking system that can certify that the grid power procured comes from a low-carbon source.

(3) Support measures for end-users

① **Criteria other than "cost" and "speed"**

Fuel procurement costs will be inevitably high in the early stages of the introduction of co-firing and single-fuel (100%) firing of low-carbon hydrogen and ammonia in existing thermal power plants. A contract for difference (CfD)-type scheme that subsidizes the difference between the price of clean hydrogen/ammonia and coal and natural gas would be effective. In Japan, such a scheme is being considered for "first-movers[2]"of the commercial hydrogen and ammonia supply chain.

In terms of early commercialization and price levels in 2030, it may be difficult for green hydrogen to compete against blue hydrogen as first-movers, given the lead time required for large-scale renewable energy projects and the production costs, including those involving water electrolysis and other processes. However, green hydrogen/ammonia can have an advantage against blue hydrogen/ammonia in terms of its low carbon intensity (CI) and lower price volatility due to its unlikeliness to be impacted by fossil fuel prices, as well as the sustainability of resources and the diversification of supplier regions and countries. These advantages could be important criteria for project screening from the perspective of energy security and building a resilient energy system. It is also important that the scheme be designed with a view to the future introduction of carbon pricing.

In addition, the stable procurement of hydrogen and its derivatives will require multiple supplier projects. As in in the early days in the history of LNG, it is likely that long-term contracts will be called for; and therefore, it is also important that support schemes are designed to accommodate the same timeframe.

② Important considerations regarding purchase commitments by end-users

When support schemes are designed to require a purchase commitment by end-users at the time of application, domestic end-users would be more inclined to conclude long-term purchase contracts for blue ammonia derived from fossil fuels, which is currently more inexpensive and promises to be available at an earlier time. In the introductory phase of hydrogen and ammonia, it will be important to reduce costs and develop a market by deploying cheaper products. Yet, it should be noted that when long-term contracts already exist, the deployment of hydrogen and its derivatives that cost more but feature lower CI values may consequently delayed. A creatively designed scheme that takes into consideration the fact that the deployment of green hydrogen could facilitate the diversification of hydrogen and ammonia supplies and thus the establishment of a stable and resilient procurement framework.

(4) Active involvement in upstream investment

2 Business operators who plan to supply clean hydrogen/ammonia by around 2030.

European and U.S. companies have been actively involved in the development of large-scale renewable energy projects in Chile. Japan should also take part in renewable energy projects and secure renewable power sources for hydrogen production. To date, government support for projects to build hydrogen and ammonia supply chains has been focused on storage and transportation technologies, and innovative technologies that reduce transportation costs. Support for upstream investments are called for in order to further reduce renewable power generation costs, which account for a large portion of the cost of producing green hydrogen

In Chile, where the electricity market is fully liberalized, it is easy for foreign companies to enter the electricity market. If projects can procure renewable power directly from dedicated power plants instead of relying on PPAs, they will have access to a more stable electric power supply.

(5) Gaining social acceptance for ammonia use

It is essential to foster understanding and cooperation among local residents regarding the safety and significance of ammonia to realize ammonia production, storage, and co-firing or power generation. In order to gain local understanding and cooperation at an early stage, the government needs to formulate the relevant laws and provide appropriate information on the handling of large amounts of toxic and flammable gases. In addition, assessment methodologies that can rationally account for the preventive measures taken against accidents and disaster risks should be established so that facilities will not be over-equipped.

(6) Introducing a tracking scheme to provide price and carbon foorprint information

Japan expects to use hydrogen and ammonia derived from various resources. To enable end-users to choose hydrogen or ammonia depending on their needs, it would be optimal for them to be able to choose based on the carbon intensity of each product, instead of based on the "color" of hydrogen. Therefore, a tracking scheme that provides information on the price and carbon footprint of each product would be useful. This type of scheme would be compatible with the electric power tracking system under consideration by the government and will facilitate the introduction of carbon pricing.

No methods currently exist for calculating domestic greenhouse gas (GHG) emissions from low-carbon fuels such as hydrogen and fuel ammonia. With a view to their widespread use in the future, calculation methods for GHG emissions from hydrogen and its derivatives should be clearly defined. In Japan, the revised Law Concerning the Rational Use of Energy requires businesses with annual energy consumption above a given level to regularly report not only on GHG emissions, but also on their non-fossil energy use and related plans. It will be necessary to define how the CO_2 emission factor for the entire hydrogen and ammonia supply chain should be evaluated in these regular reports.

It is also important to establish a system that allows all parties involved to engage in projects with faith in the policy framework. The calculation of CO_2 emissions across the supply chain is a concern not only for the demand side but also for exporting countries. Whether or not a producer can be sure that the clean hydrogen and ammonia to be produced will meet consumers' needs or the standards determined by the importing country may affect the approval decision made by exporting country governments and financial institutions. Definitions and conditions for renewable hydrogen have already been announced in Europe and the United Kingdom.

(7) Building G to G frameworks

It is important that bilateral agreements be reached on the attribution and cost-sharing of greenhouse gases emitted across the supply chain, as well as on the CO_2 emissions calculation methodology.

With the global inclination toward resource nationalism, the development of bilateral and multilateral frameworks for cooperation on energy and natural resources will become increasingly important. Even in Chile, which has been a world leader in market liberalization, there are many calls for strengthening the authority of the state in resource management, as evidenced by the proposed inclusion of the abolition of water rights in the draft constitutional amendment which was rejected in September 2022.

As the world searches for solutions to achieve net-zero emissions in 2050, the race to establish green hydrogen supply chains will intensify in the medium to long term. In addition to Japanese government support for operators of green hydrogen supply chain projects in countries including Chile, a support mechanism that encourages the domestic deployment in Chile of cutting-edge technologies developed by Japanese companies would also be effective. It is also important for the Chilean government, as the supplier country, to support the initial phases of projects. Support from both countries is essential for the early realization of an international green hydrogen supply chain from Chile to Japan.

1 BACKGROUND AND OBJECTIVES

In November 2021, IEEJ(2021)[3] evaluated the economics and GHG emissions of establishing an international supply chain to extract hydrogen from liquefied hydrogen, ammonia, or MCH imported from Australia, Saudi Arabia, the United States, and Chile to Japan. The study revealed that under given conditions, green ammonia produced in northern and southern Chile was highly competitive.

A long and narrow country stretching 4,300 km north to south and 180 km from east to west, Chile is ideal for renewable power generation. Solar power in Antofagasta[4] in northern Chile and wind power in Magallanes[5] in southern Chile have outstanding high capacity factors contributing to making Chile's renewable energy prices among the most cost competitive in the world. In November 2020, the Chilean government formulated the "National Green Hydrogen Strategy," the first of its kind in South America, with an aim to achieve carbon neutrality by 2050 by utilizing its renewable energy resources and to develop a new export industry to follow its mining industry. The strategy has the following three main objectives: i) Develop water electrolysis capacity of 5GW by 2024; ii) supply the world's most low-cost green hydrogen (USD1.5/kg); iii) Become the world's third largest green hydrogen exporter in 2040. This has been followed by MOUs between the Minstry of Energy and the ports of Rotterdam and Amsterdam, as well as Singapore and Germany, with a view to strengthen cooperation with hydrogen importing countries and build international greenhydrogen supply chains. In April 2023, the Ministry concluded a Memorandum of Cooperation (MOC) on energy transition with the Ministry of Economy, Trade and Industry, Japan. Furthermore, the Green Hydrogen Action Plan 2023-2030 is scheduled to be released by the end of 2023. Chile is currently advancing the development of laws and regulations necessary for the domestic production, transportation, and storage of hydrogen and ammonia, led by the Ministry of Energy, the Ministry of Environment, and the Chile Industrial Development Corporation (CORFO).

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3 The Institute of Energy Economics (2021) "Study on the Economics of the Green Hydrogen InternationalSupply Chain" https://eneken.ieej.or.jp/data/9882.pdf

4 The Atacama Desert in norther Chile has the highest annual global horizontal irradiance (GHI) in the world, with of over 2,800 kWh/m^2 . The National Energy Policy (NEP) 2050 envisions the installation of more than 20 GW of additional installed capacity by 2050.

5 The Atacama Desert and other northern and southern areas of Chile have wind resources of more than 14 m/sec (100 m altitude); NEP 2050 targets the installation of more than 20 GW in wind power capcity by 2050.

Based on the results of the IEEJ (2021) study, an in-depth study was conducted from April 2022 through February 2023 with the cooperation of Japanese private companies, including electric power companies, a shipping company, an engineering company, and a trading company. The cost structure of the green ammonia supply chain from Chile to Japan was further analyzed to evaluate the feasibility of building a green ammonia supply chain and identify policy challenges and solutions.

2 SCOPE AND METHODOLOGY OF STUDY

This study analyzed the cost structure of a green ammonia supply chain where hydrogen is produced by water electrolysis using renewable energy in Chile, the gree hydrogen is used to produce green ammonia, which is transported to Japan by sea, and is used for 20% co-firing with coal at two coal-fired power plants (500 MW and 1GW) owned by power generation utilities in Japan. The total green ammonia demand at the target power plants was assumed to be 800,000 ton/y.

We assumed two projects – one in northern Chile and one in southern Chile. The most economically optimal ammonia production plant design was simulated based on the abovementioned assumed demand. In Antofagsta Province in northern Chile, we assumed that renewable power would be procured through power purchase agreements (PPAs) and that the variability of these renewable power sources, assumed based on hourly solar power generation profiles in Antogasta, would be balanced by grid electricity, using energy attribute certificates (EACs) to prove its green attributes of the electricity. Similarly, in southern Chile, wind power would procured through PPAs and hydrogen gas turbines would provide backup power for ammonia plant operations. We also estimated the impact on power generation costs that would be expected if 20% ammonia were to be co-fired with coal in coal-fired power plants in Japan. The scope of the study and the major factors considered are presented in Table 1.

Table 1. Scope of study

Supply chain phase		Major factors considered
Production (Chile)	Renewable power generation	· Electric power source (incl backup power) · Addersing output variability · Energy storage
	Green hydrogen production	· Water electrolyzers
	Ammonia production	· Ammonia production equipment
	Overally production process	· Optimization of power source – ammonia production
Transport (Ocean)	Export terminal (New construction or repurposement)	· Specifications of port facilities
	Shipping	· Export method, navigation routes, volumes
Use (Japan)	Receiving ports in Japan	· Repurposing of domestic ports
	Ammonia co-firing in power plants in Japan	· Impact on power generation costs

2.1 GREEN AMMONIA PRODUCTION

The Haber-Bosch process was used for the production of green ammonia (Figure 1), in which hydrogen produced by water electrolysis using renrewable energy, is reacted with nitrogen separated from air.

The production cost of green ammonia accounts for a large portion of the overall cost of the green ammonia supply chain; and therefore, it is necessary to optimize the combination of various factors, such as the procurement of renewable energy, balancing output variability, and capacity factor of the production facilities. In particular, the water electrolyzer, hydrogen gas holder, and hydrogen compressor account for 70-80% of the construction cost. In this study, data was collected on the annual profile of renewable power generation, electricity procurement prices, and specifications and costs of water electrolyzers and ammonia production facilities. Based on this data, the optimal equipment configuration and operation patterns were examined[6].

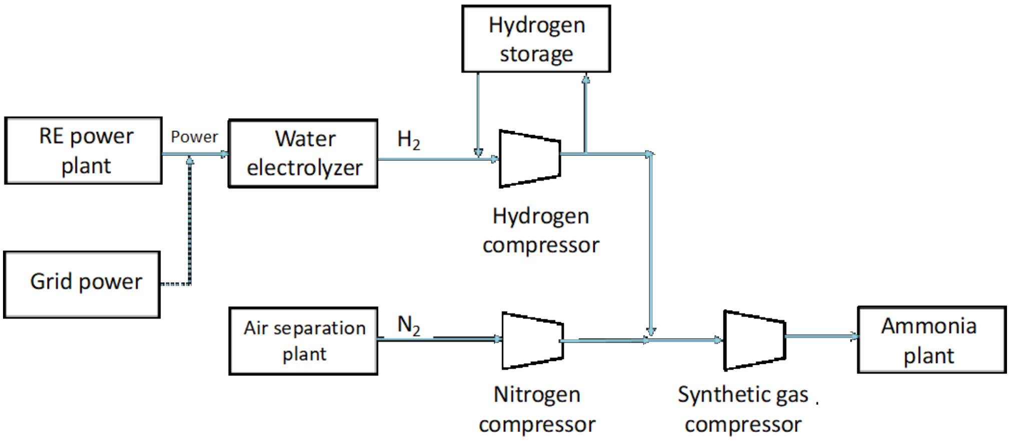

Figure 1. **Block flow of green ammonia productions**

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6 A Japanese engineering company provided their support in the calculation and estimation of specifications for each facility and in considering the optimal facility configuration and operating concept. Japanese trading companies and shipping companies assisted providing the data for the other specifications (profiles and procurement prices of renewable power generation in northern and southern Chile, grid power procurement prices, estimated capital costs for desalination facilities, outsourcing costs for distribution facilities, capital costs for storage batteries, hydrogen gas turbine power generation costs, and marine transportation costs). Publicly accessible data was also used.。

In northern Chile, solar power is not available at night and therefore, the following measures were considered: i) increasing the solar power generation capacity to store energy in storage batteries or hydrogen holders for use at night; ii) using grid electricity (with energy attribute certificates (EACs)[7]); iii) controlling the operation of ammonia production facilities; and iv) a combination of these measures.

Since there is no electric power grid in southern Chile, hydrogen holder will be needed in order to absorb fluctuations in hydrogen production due to the variability of wind power. Therefore, the optimization of hydrogen storage pressure and capacity were studied for each type of equipment, including gas holders, spheric tanks, and bullet tanks. In addition, we analyzed two cases: 1) the hydrogen volume stored in the hydrogen holders is minimized based on the assumption that the ammonia production facility would be shut down for a certain period of time when wind enough wind blow is not available; and 2) the total capacity of the hydrogen holders is sufficient to maintain continuous ammonia production regardless of wind conditions. Furthermore, we compared the cases in which hydrogen gas turbines or storage batteries are employed as backup power sources for the ammonia plant.

2.2 SHIPPING OF AMMONIA

For the shipping of ammonia, around 60 patterns were considered. These included different combinations of loading ports (northern and southern Chile), discharging ports in Japan (direct shipping, multiple port discharge, and secondary transport using domestic vessels (explained below), and vessel sizes.

Currently, mid-size LPG carriers (tank size: 35,000-42,000 m^3, capable of transporting ammonia), called MGCs (Mid-size Gas Carriers), are mainly used for long-distance ocean transportation of ammonia. MGCs can only carry less than around 30,000 tons of ammonia per voyage. In order to meet future increases in the demand for shipping massive volumes of ammonia, it will be necessary to increase the loadable quantity of vessels capable of carrying ammonia. Hence, we examined the possibility of increasing the transport volume of ammonia per voyage between Chile and Japan, and thus lowering the transportation cost per unit. We

7 Today in Chile, EACs can be acquired free of charge for renewable power. However, the introduction of a nationwide guarantee of origin system is under consideration and EACs may eventually need to be purchased.

analyzed the economics and the number required regarding the following vessel types: MGCs, LGCs (Large Gas Carriers), VLGCs (Very Large Gas Carriers), and ULGCs (Ultra Large Gas Carriers). Since ammonia-fueled main engines are still in the development stage, the specifications for existing low-sulfur fuel oil (VLSFO)-fueled vessels were applied.

As for shipping routes, we used the Great Circle Route between Chile and Japan, and optimized it based on the conditions at each target port. We made considered three patterns regarding discharging port, as aforementioned: i) direct shipping to power plant; ii) multiple port discharge; and iii) secondary transport using domestic vessels (Table 2).

Table 2. Description of shipping patterns

Shipping pattern	Conditions for receiving ports
i) Direct shipping to power plant	The power plant premises have sufficient unused land to accommodate fuel ammonia storage tanks and related facilities, and have port facilities capable of directly receiving ammonia vessels.
ii) Multiple port (power plant) discharge	When it is difficult for one power plant to receive all of the ammonia carried by a vessel, the transportation efficiency can be improved by receiving the ammonia at different power plants.
iii) Secondary transport using domestic vessels	Develop a port outside the power plant where other industries are concentrated for primary discharge, and deliver to power plants via secondary transport using domestic vessels.

2.3 DOMESTIC USE OF AMMONIA IN JAPAN

In examining the generation cost, the unit cost of electric power generation was estimated by aggregating the costs of coal and ammonia, assuming the case where an ammonia co-firing facility is added to an existing coal-fired power plant in Japan. For existing coal-fired power plants, parameters were adjusted according to the capacity and efficiency of the power generation facilities assumed to be used by each power utility, based on the power generation costs concluded by the Power Generation Cost Analysis Working Group[8]. For facilities retrofitted for ammonia co-firing, capital costs were calculated based on the capital costs for ammonia-retrofitted facilities estimated by J-Power (2019)[9] (Table 3).

8 Power Generation Cost Analysis Working Group (2021) "List of data for each power source" (Material 3 delivered at the 8th meeting of the Power Generation Cost Analysis Working Group, Advisory Committee for Natural Resources and Energy (September 8, 2021)) https://www.enecho.meti.go.jp/committee/council/basic_policy_subcommittee/mitoshi/cost_wg/pdf/cost_wg_20210908_02.pdf

9 J-Power (2019) *Final report: SIP (Cross-ministerial Strategic Innovation Program); Theme: Energy Carriers; R&D theme: "Developing technologies related to* CO_2*-free hydrogen applications and ammonia production,*

Table 3. Scope of power generation cost estimations

	Component of power generation costs	Cost items	Source
Ammonia	Fuel cost	Fuel ammonia cost	Ammonia price before receiving at power plant
	Capital cost	Receiving, storage, and discharge faciltiies	J-Power (2019)
		Power generation facility	
Coal-fired power plant	Fuel cost	Coal cost	Assumed Coal CIF price
	Capital cost / O&M cost	Capital cost (existing coal-fired power plant)	Power generation cost analysis WG
		O&M costs	

storate and transport"; Research title: "Study on technologies related to the supply chain for CO_2-free ammonia as a thermal power plant fuel", p.13 https://www.jst.go.jp/sip/dl/k04/end/team3-19.pdf

3 MAJOR FINDINGS

3.1 AMMONIA SUPPLY COSTS

As a result of our simulations for ammonia production, we concluded that the optimal annual production capacity would be one million tons of ammonia in northern Chile, and 780,000 tons, in southern Chile using an ammonia plant with a nominal capacity of 3,000 ton/d.

In the north, we found that the Levelized Cost of Ammonia (LCOA) would be minimized when ammonia production facilities were operated at full capacity using grid power during the night. The Levelized Cost of Electricity (LCOE) can be lowered by procuring relatively inexpensive wind power at night. However, when wind power cannot be procured, the LCOE will be affected by the spot price of the green electricity, which will be higher. In the case of developing a dedicated solar power plant in northern Chile, the costs pertaining to a dedicated transmission line (extending across more than 100km) from the power plant to the hydrogen and ammonia production facilities would be necessary. In the south, it was concluded that the best case scenario would be to operate the ammonia plant in accordance with the wind profile without shutting down the production facility, thus using a hydrogen gas turbine as a backup power source.

As for the maritime transport of ammonia, simulation results revealed that the number of vessels required would be an estimate of 0.9-2.5 VLGCs or 0.8-2.3 ULGCs. However, since the market for ammonia carriers is smaller and less liquid than that for other large cargo ships, the required shipping capacity may not be available. In the commercialization phase, the above number of vessels would need to be newly built as dedicated vessels for the project, and such shipbuilding costs would also need to be taken into account.

The most effective shipping pattern was multiple port discharge, when considering the investment amounts needed for tank infrastructure.

The development of new port facilities to discharge ammonia or load it on vessels would entail administrative procedures to gain permits and approvals and marine construction that would require enormous amounts of time and money. Therefore, the ideal solution would be to be able to make maximum use of existing port facilities, with minimal retrofits of jetties and berths. However, southern Chile is home to very limited port infrastructure.

Figure 2 compares the results of IEEJ(2021) with the CIF Japan price derived from the estimated ammonia production price, port costs, and maritime transportation costs. Although a simple comparison cannot be made due to difference in various assumptions[10], no significant difference was found between this study and IEEJ(2021) in the sum of capital and power generation costs for ammonia production or the port and port and maritime transportation costs. This applies for both solar power in northern Chile and wind power in southern Chile. It was also reconfirmed that maritime transportation costs have limited impact on the total cost. It is important to note that IEEJ(2021) did not consider other expenses, including labor costs, margins, and taxes, whichwould be included in a real project or storage facility costs, such as those for the hydrogen tanks that would be employed to balance the variability of renewable power. Hence, the fact that the sum of capital costs and electric power costs are comparable between this study and IEEJ(2021), imply that further cost reductions could be possible in actual implementation.

Figure 2 also presents potential cost reductions (reduction measures to be easily taken) based on the experience of companies that cooperated in the study.

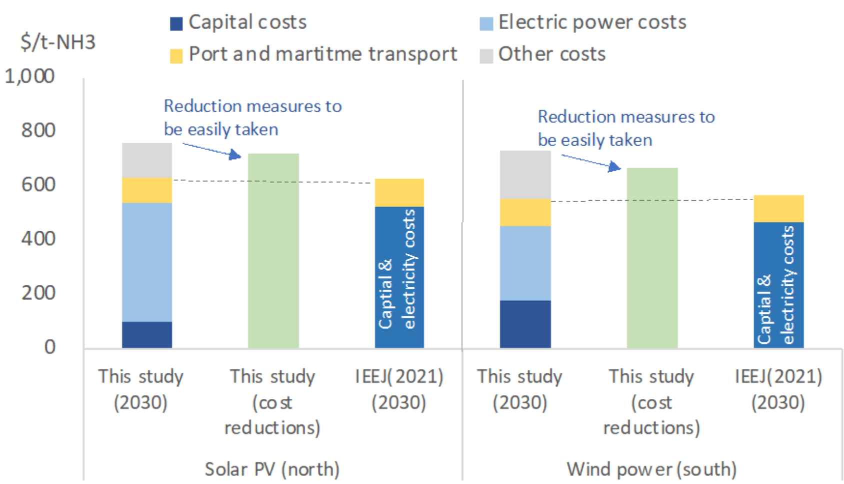

Figure 2. Green ammonia production costs

Note: Electric power procurement costs in northern Chile include solar power (PPA) and grid power (with EACs).

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10 IEEJ(2021) concludes that green ammonia production costs would be 628 USD/t-NH_3 in the north (solar PV) and 568 USD/t-NH_3 in the south (wind power), but does not include various costs, including auxiliary costs related to electric power, which were considered in this in-depth study; and therefore, direct comparisons cannot be made.

3.2 DOMESTIC USE OF AMMONIA IN JAPAN

Based on the results above, we performed a sensitivity analysis of unit power generation costs based on coal and ammonia prices (Figure 3). We assumed that 20% ammonia would be co-fired in a coal-fired power plant.

Figure 3 shows that compared to blue ammonia co-firing, which is affected by the price volatility of both coal and the natural gas used to produce blue ammonia, co-firing green ammonia can contribute to limiting the impact of coal price volatility. Given that tax incentives for hydrogen-related projects are currently under consideration in Chile and that there are regional tax incentives in place, particularly in the southern region, costs may be further reduced depending on future developments.

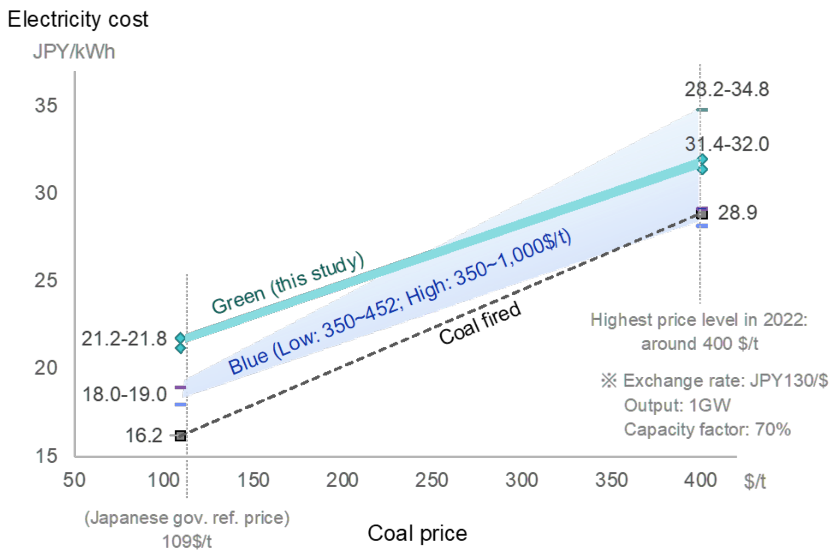

Figure 3. Sensitivity analysis of unit power generation cost based on coal price and NH3 price

Note: For blue ammonia, the lower price range is assumed to be 350-452 USD/t (ranging from the government target price to assumptions by the Power Generation Cost Analysis Working Group[11]) and the higher price range is assumed to be 350-1,000 USD/t (ranging from the government target price to the highest ammonia price level in fiscal 2022). Coal prices are based on the government reference price[12] given by the Power Generation Cost Analysis Working Group under the Advisory Committee for Natural Resources and Energy and the high price (around 400 USD/t) is based on JOGMEC (2022)[13].

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11 Power Generation Cost Analysis Working Group, *op. cit.*

12 *Ibid.*

13 JOGMEC "Current Topics Coal Price Trends (August 2022)" https://coal.jogmec.go.jp/content/300379777.pdf

3.3 CARBON FOOTPRINT OF AMMONIA

Not only the costs but also the CO_2 emission factor will be important factors of ammonia. Figure 4 exhibits the carbon footprint of the entire green ammonia supply chain between Chile and Japan. Since the project in northern Chile uses a combination of solar power and grid electricity offset by EACs and the project in southern Chile is based entirely on wind power, there are CO_2 emissions involved with the ammonia production or export ports. Although there are some CO_2 emissions from the utilities at the import ports in Japan, the largest CO_2 emission factor across the supply chain is attributed to maritime transportation, with an emission factor of 0.15-0.16 kg-CO2/kg-NH_3 when the vessel fuel used is low-sulfur heavy fuel oil (VLSFO). This is still far below the CO_2 emission threshold of 0.84 kg-CO2e/kg-NH_3 for ammonia production only, which was set in Japan's revised Basic Hydrogen Strategy[14]. Furthermore, when green ammonia is used as shipping fuel, the carbon footprint of the entire supply chain becomes extremely small.

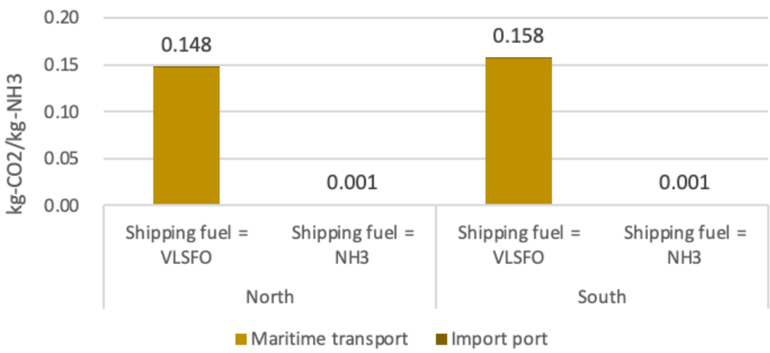

Figure 4. Carbon footprint of entire green ammonia supply chain

14 Ministerial Council on Renewable Energy, Hydrogen and Related Issues (2023) *Draft Basic Hydrogen Strategy*, https://www.cas.go.jp/jp/seisaku/saisei_energy/kaigi_dai4/siryou1-2.pdf

4 CHALLENGES AND PROPOSALS

4.1 BUILDING THE BUSINESS ENVIRONMENT IN CHILE

Given the high capacity factor and low cost of renewable electricity in Chile, green hydrogen and its derivatives produced in Chile potentially bears world-class price competitiveness, but calls for improvements in the business environment, including institutional support. Even with low renewable electricity generation costs, the actual procurement cost could end up being high due to accompanying costs, such as power transmission costs. In addition, it is necessary to secure a competitive advantage that includes the costs pertaining to land acquisition for port and plant development, as well as administrative costs. Chile is expected to have much competition as a hydrogen supplier, including other Latin American countries, the United States, Australia, and Middle Eastern countries. Therefore, it will be important to provide financial support such as subsidies and tax incentives, and to streamline licensing and approval processes to the maximum extent possible. For example, the United States has announced ambitious support measures under the Inflation Reduction Act (IRA), and the EU, under "RePOWER EU," and it is inevitable that comparisons will be made among the hydrogen business environment of different countries.

A demonstration of policy support for the further reduction of grid power costs and for the development of common infrastructure (transmission lines, port facilities, etc.), as well as subsidies, tax incentives, deregulation, and procedural streamlining, including clarifying and accelerating the procedures and guidelines for acquiring environmental permits and approvals and developing one-stop project approval procedures, would be reassuring to project developers and investors considering long-term projects in Chile.

4.2 LONG-TERM PROCUREMENT OF LOW-CARBON GRID POWER

Large-scale renewable energy projects require long lead times before they can be operational. Therefore, an urgent challenge would be building a system that allows grid electricity with a low carbon footprint to be used for hydrogen production for the early establishment of hydrogen production projects. However, with a population of 19.68 million people, Chile does not have a large domestic electricity demand; and therefore, the current grid capacity is not large enough to supply power to multiple large-scale hydrogen projects. Effective measures include not only reinforcing transmission lines, but also effectively using currently curtailed electric power through charge surplus power during the day for discharge during the nighttime, as well as promoting the employment of water electrolyzers to provide grid flexibility under the new law on energy storage and electromobility. Furthermore, grid power would need to be certified by a nationwide tracking system meeting international standards that proves that the electric power used was produced from a renewable energy source.

4.3 SUPPORT MEASURES FOR END-USERS

CRITERIA OTHER THAN COST AND SPEED

Fuel procurement costs will be inevitably high in the early stages of the introduction of co-firing and single-fuel (100%) firing of low-carbon hydrogen and ammonia in existing thermal power plants. A contract for difference (CfD)-type scheme that subsidizes the difference between the price of clean hydrogen/ammonia and fossil fuels, such as coal and natural gas would be effective. In Japan, such a scheme is being considered for "first-movers[15]"of the commercial hydrogen and ammonia supply chain.

Green hydrogen/ammonia can have an advantage against blue hydrogen/ammonia in terms of its low carbon intensity (CI) and lower price volatility because it is unlikely to be impacted by fossil fuel prices. However, in terms of early commercialization and price levels in 2030, it may be difficult for green hydrogen to compete against blue hydrogen, given the lead time required for large-scale renewable energy projects and the production costs, including those involving water electrolysis and other processes. Therefore, it may miss the opportunity to receive government support. From the perspective of energy security and building a resilient energy system, the sustainability of resources and the diversification of supplier regions and countries could also be included in the criteria for project screening. It is also important that the scheme be designed with a view to the future introduction of carbon pricing.

In addition, the stable procurement of hydrogen and its derivatives will require multiple projects that promise to supply hydrogen. As in in the early days in the history of LNG, it is likely that long-term contracts will be called for; and therefore, it is also important that support schemes are designed to accommodate the same timeframe.

15 Business operators who plan to supply clean hydrogen/ammonia by around 2030.

IMPORTANT CONSIDERATIONS REGARDING PURCHASE COMMITMENTS BY END-USERS

When support schemes are designed to require a purchase commitment by end-users at the time of application, domestic end-users would be encouraged to conclude long-term purchase contracts for blue ammonia derived from fossil fuels, which is currently more inexpensive and promises to be available at an earlier time. In the introductory phase of hydrogen and ammonia, it will be important to reduce costs and develop a market by deploying cheaper products. Yet, it should be noted that when long-term contracts already exist, the deployment of hydrogen and its derivatives that cost more but feature lower CI values may consequently delayed. A creatively designed scheme that takes into consideration the fact that the deployment of green hydrogen could facilitate the diversification of hydrogen and ammonia supplies and thus the establishment of a stable and resilient procurement framework.

4.4 ACTIVE INVOLVEMENT IN UPSTREAM INVESTMENT

European and U.S. companies have been actively involved in the development of large-scale renewable energy projects in Chile. Japan should also take part in renewable energy projects and secure renewable power sources for hydrogen production. To date, government support for projects to build hydrogen and ammonia supply chains has been focused on storage and transportation technologies, and innovative technologies that reduce transportation costs. Support for upstream investments are called for in order to further reduce renewable power generation costs, which account for a large portion of the cost of producing green hydrogen.

In Chile, where the electricity market is fully liberalized, it is easy for foreign companies to enter the electricity market. If projects can procure renewable power directly from dedicated power plants instead of relying on PPAs, they will have access to a more stable electric power supply.

4.5 GAINING SOCIAL ACCEPTANCE FOR AMMONIA USE

The handling of large ammounts of ammonia, which is a toxic gas, requires not only preventive measures against leakage but also measures to minimize the impact of any leakage that may occur. In addition, in order to comply with legal standards regarding the layout of ammonia tanks, including the spacing between tanks, there will be a need to secure more land around exisiting power plants, as there is usually very limited unused land on the premises of most facilities

It is essential to foster understanding and cooperation among local residents regarding the safety and significance of ammonia to realize ammonia production, storage, and co-firing for power generation. In order to gain local understanding and cooperation at an early stage, the government needs to formulate the relevant laws and provide appropriate information on the handling of large amounts of toxic and flammable gases[16]. In addition, assessment methodologies that can rationally account for the preventive measures taken against accidents and disaster risks should be established so that facilities will not be over-equipped.

4.6 INTRODUCING A TRACKING SCHEME TO PROVIDE PRICE AND CARBON FOOTPRINT INFORMATION

Japan expects to use hydrogen and ammonia derived from various resources. To enable end-users to choose hydrogen or ammonia depending on their needs, it would be optimal for them to be able to choose based on the carbon intensity of each product, instead of based on the "color" of hydrogen. Therefore, a tracking scheme that provides information on the price and carbon footprint of each product would be useful. This type of scheme would be compatible with the electric power tracking system under consideration by the government and will facilitate the introduction of carbon pricing.

No methods currently exist for calculating domestic greenhouse gas (GHG) emissions from low-carbon fuels such as hydrogen and fuel ammonia. With a view to their widespread use in the future, calculation methods for GHG emissions from hydrogen and its derivatives should be clearly defined. In Japan, the revised Law Concerning the Rational Use of Energy requires businesses with annual energy consumption above a given level to regularly report not only on GHG emissions, but also on their non-fossil energy use and related plans. It will be necessary to define how the CO_2 emission factor for the entire hydrogen and ammonia supply chain should be evaluated in these regular reports.

16 As of July 2023, Chile is conducting a participatory process to formulate Action Plan 2023-2030 of the National Green Hydrogen Strategy. Workshops are being held across the country, engaging different stakeholders and conducting outreach activities on hydrogen and derivatives to local residents. The government is also preparing to legally define ammonia as a fuel.

It is also important to establish a system that allows all parties involved to engage in projects with faith in the policy framework. The calculation of CO_2 emissions across the supply chain is a concern not only for the demand side but also for exporting countries. Whether or not a producer can be sure that the clean hydrogen and ammonia to be produced will meet consumers' needs or the standards determined by the importing country may affect the approval decision made by exporting country governments and financial institutions. Definitions and conditions for renewable hydrogen have already been announced in Europe and the United Kingdom.

4.7 BUILDING G TO G FRAMEWORKS

It is important that bilateral agreements be reached on the attribution and cost-sharing of greenhouse gases emitted across the supply chain, as well as on the CO_2 emissions calculation methodology.

With the global inclination toward resource nationalism, the development of bilateral and multilateral frameworks for cooperation on energy and natural resources will become increasingly important. Even in Chile, which has been a world leader in market liberalization, there are many calls for strengthening the authority of the state in resource management, as evidenced by the proposed inclusion of the abolition of water rights in the draft constitutional amendment which was rejected in September 2022.

As the world searches for solutions to achieve net-zero emissions in 2050, the race to establish green hydrogen supply chains will intensify in the medium to long term. In addition to Japanese government support for operators of green hydrogen supply chain projects in countries including Chile, a support mechanism that encourages the domestic deployment in Chile of cutting-edge technologies developed by Japanese companies would also be effective. It is also important for the Chilean government, as the supplier country, to support the initial phases of projects. Support from both countries is essential for the early realization of an international green hydrogen supply chain from Chile to Japan.

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