Chapter 4

Review of Hydrogen Transport Cost and Its Perspective (Liquefied Hydrogen)

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Chapter 4

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1. Introduction

In Japan, CO_2-free hydrogen energy has been gaining momentum since the endorsement of the government's 4th Strategic Energy Plan in 2014, which identified hydrogen as an important energy solution of the future.

Kawasaki Heavy Industries, Ltd. is developing world-leading technologies to realise the hydrogen society. These include the liquefier, the storage tank, the supply systems, the liquefied hydrogen carrier ships, and the hydrogen gas turbines. Kawasaki can contribute to decarbonisation by promoting international hydrogen supply chains through hydrogen-related technologies.

2. Liquefied Hydrogen Supply Chain for Decarbonisation

2.1. The concept of liquefied hydrogen supply chain

The conceptual diagram of the liquefied hydrogen energy supply chain by Kawasaki is shown in Figure 4.1. Kawasaki plans to produce hydrogen overseas from affordable resources and bring liquefied hydrogen to Japan. This scheme of hydrogen supply chain is very similar to that of the liquefied natural gas (LNG) supply chain.

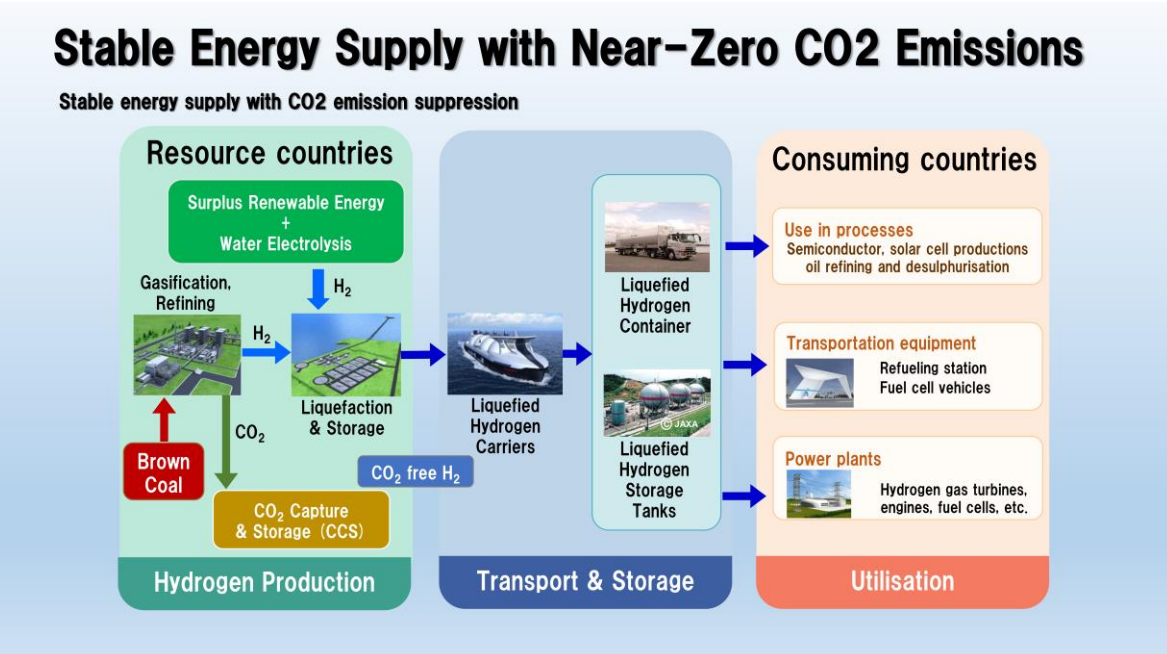
Due to the method of producing hydrogen, we can promote a CO_2-free hydrogen supply chain worldwide. We are looking for a suitable place to produce hydrogen reasonably from fossil fuel with carbon capture utilisation and storage (CCUS) and renewable energy such as solar, wind, or hydropower (Figure 4.2.).

To transport and store hydrogen efficiently, the produced hydrogen gas will be liquefied. The liquefied hydrogen will then be loaded in special liquid hydrogen carrier ships and transported to Japan.

Hydrogen is used for various purposes like feedstock, fuel cell vehicles (FCVs), distributed power and heat generation, and large utility power generation. Regarding the amount of consumption, a hydrogen power station with a capacity of approximately 1 GW consumes 220,000 tonnes of hydrogen in a year. This is equivalent to the total annual fuel for 3 million FCVs.

By realising a large-scale CO_2-free hydrogen supply chain, hydrogen cost will decrease and become competitive. This can promote the deployment of FCVs, hydrogen stations, and other hydrogen-energised equipment. We believe this large-scale supply chain will accelerate the realisation of the hydrogen economy and sustainable future.

Figure 4.1: Conceptual Diagram of the Hydrogen Energy Supply Chain by Kawasaki Heavy Industries, Ltd



Source: Author.

Figure 4.2: Expected CO_2-Free H2 Supply Chain

Source: Author.

2.2. Advantages of liquefied hydrogen carriers

The advantages of liquefied hydrogen carriers are shown in Figure 4.3. The volume of liquefied hydrogen is 1/800 that of gaseous hydrogen. Therefore, liquefied hydrogen is suitable for transporting a large amount of hydrogen overseas with high efficiency.

Liquefied hydrogen has a purity of 99.999% or higher and can be directly supplied to fuel cells only by evaporating it without refining, which needs domestic energy.

When hydrogen is burned, only water, and not CO_2, is emitted. Therefore, the use of hydrogen can contribute to environmental measures.

Hydrogen is also not toxic and has no greenhouse effect; thus, an excellent substance in terms of health and safety.

The scheme of liquid hydrogen supply chain is like that of the supply chain of liquefied natural gas (LNG). LNG, which is currently distributed all over the world, was once very expensive. However, as years pass and the volume of distribution increases, it has become relatively affordable energy. Therefore, hydrogen can potentially and significantly decrease the cost in the future. Those are the reasons we chose liquid hydrogen as a carrier.

Figure 4.3: Advantages of Liquefied Hydrogen Carrier

Source: Author.

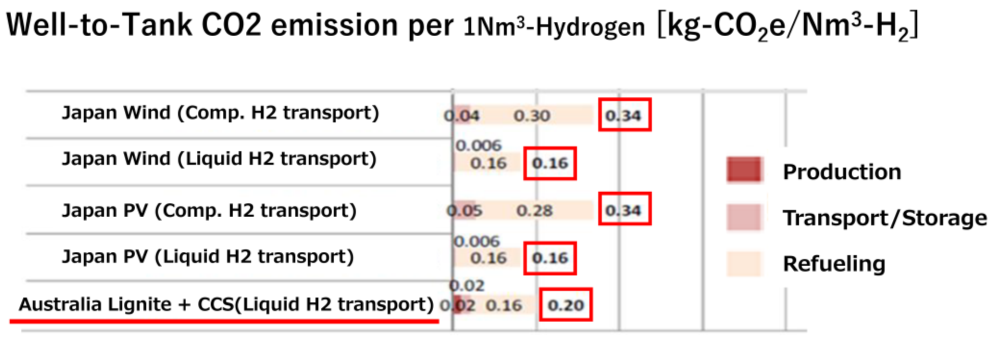
2.3. Life-cycle analysis of liquefied hydrogen supply chain

Figure 4.4 shows the life-cycle analysis (LCA) conducted by the Mizuho Information & Research Institute, Inc.[2] This shows well-to-tank CO_2 emissions in each process of hydrogen production, which uses renewable energy and brown coal (lignite).

CO_2 emissions from liquefied hydrogen produced by brown coal with carbon capture and storage (CCS) are at the same level as the one from renewable energy–derived hydrogen.

Especially when hydrogen is carried by a liquefied hydrogen carrier ship, boiled-off hydrogen gas can be used as a fuel to propel the ship. This technology has already been adapted to the LNG carrier. Therefore, unlike other carriers, the liquefied hydrogen supply chain is a completely CO_2-free supply chain, including the transport process.

Figure 4.4: Life-Cycle Analysis Conducted by Mizuho Information & Research Institute



Source: Mizuho Information & Research Institute, Inc. (2016).

3. Overview of Hydrogen Energy Supply Chain Pilot Project between Australia and Japan

Together with our private and public sector partners, we launched the world's first pilot demonstration project regarding liquefied hydrogen energy supply chain between Australia and Japan. Under this flagship initiative, we will establish an integrated supply chain for CO_2-free hydrogen produced from Australian brown coal to be exported to Japan (Nishimura et al., 2015). The governments of Japan, Australia, and Victoria State have invested in the project alongside a consortium of reputable private sector companies.

In 2020–2021, this pilot project will demonstrate brown coal gasification and hydrogen purification at Latrobe Valley in Australia, hydrogen liquefaction and storage of liquefied hydrogen at Hastings, marine transportation of liquefied hydrogen from Australia to Japan, and unloading of liquefied hydrogen in Japan (Takaoka et al., 2017).

About half of the world's total coal resources is brown coal. However, it is relatively bulky and has low calorie due to its extremely high moisture content. As it runs the risk of igniting spontaneously upon contact with air when it is dried, it is not suitable for transportation and

[2] https://www.mizuho-ir.co.jp/publication/report/2016/pdf/wttghg1612.pdf (in Japanese).

storage in its raw form. Thus, it is limited to local use; there is no international market for brown coal.

We can mass-produce affordable and CO_2-free hydrogen from this unused resource.

Diverting the existing technologies to construct LNG marine carriers for land transport and for the storage of liquefied hydrogen, Kawasaki developed a world's-first cargo containment system for liquefied hydrogen transportation on a marine carrier. The liquefied hydrogen carrier ship cruises around 9,000 km (Takaoka et al., 2019).

This is the first new energy terminal in Japan. The pilot project site is located on a 10,000 m² area of land in the northeast section of Kobe Airport Island in the Port of Kobe, where the liquefied hydrogen storage tank and unloading facilities are built. The loading arm system unloads the liquefied hydrogen from the carrier into an on-land liquefied hydrogen storage tank, whilst maintaining a temperature of –253℃.

3.1. Structure of the Australia pilot demonstration

The structure of this pilot demonstration project is shown in Figure 4.5. This pilot project has two portions. One is the portion of the New Energy and Industrial Technology Development Organization (NEDO) (two blue frames) and the other is the Australian portion (orange frame). The NEDO portion covers the gasification in Australia, the hydrogen carrier, and the unloading terminal in Japan.

This portion is supported by NEDO and is performed by HySTRA (CO_2-free Hydrogen Energy Supply-Chain Technology Research Association). HySTRA aims to establish and demonstrate technologies, which are hydrogen production, oversea transport, and unloading. HySTRA comprises the following seven companies: J-Power, Kawasaki, Iwatani, Shell Japan, Marubeni, JXTG Nippon Oil & Energy, and Kawasaki Kisen.

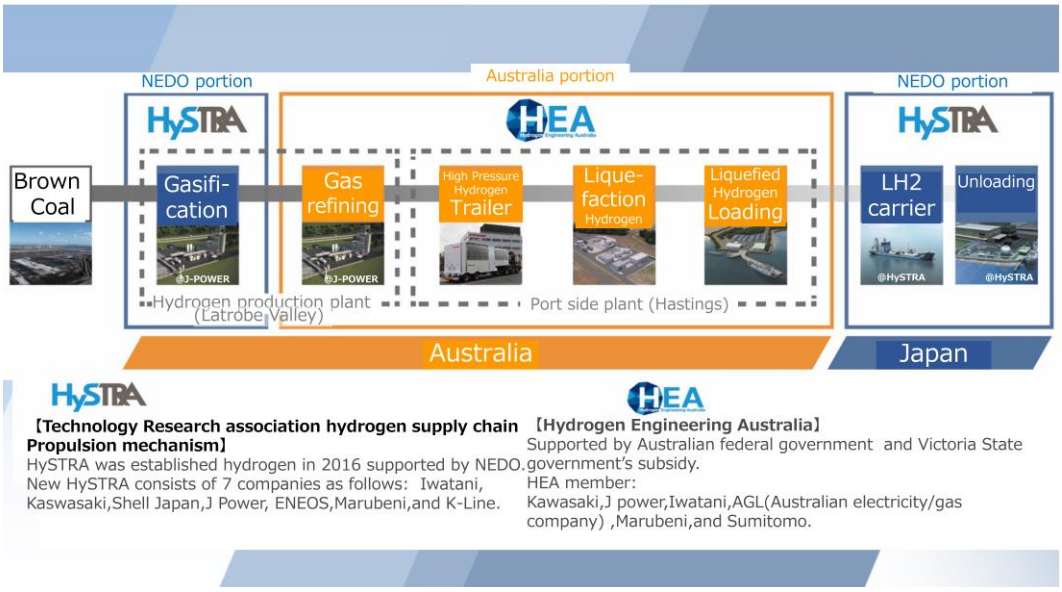
J-Power, which is currently developing an integrated coal gasification combined cycle (IGCC) system, will demonstrate technology for the gasification of brown coal. Kawasaki, Iwatani, and Shell Japan will work together to demonstrate technology for long-range mass transport and cargo handling of liquefied hydrogen.

Kawasaki, which has the cryogenic technology for LNG storage tanks and the receiving terminals as well as equipment for the rocket launch complex on Tanegashima, will build the pilot carrier ship for liquefied hydrogen and construct the unloading terminal. Meanwhile, Iwatani, which is Japan's only producer and supplier of liquefied hydrogen, will operate this loading–unloading terminal for demonstration tests. Shell Japan, a subsidiary of Royal Dutch Shell experienced with LNG supply chains and carrier operation, will operate the liquefied hydrogen carrier ship.

Marubeni and JXTG Nippon Oil & Energy are exploring the commercialisation of CO_2-free hydrogen energy supply chain technology. Kawasaki Kisen assists in the safe transport of liquefied hydrogen.

On the other hand, the scope of the Australian portion is gas purification, hydrogen liquefaction, and the loading terminal for the hydrogen energy supply chain pilot project. Those are being delivered by a consortium of the top energy and infrastructure-related companies of Japan and Australia, with the full support of the Victoria state government and the Australia federal government. Together with Kawasaki and Hydrogen Engineering Australia, the consortium partners include J-Power, JPLV (J-Power Latrobe Valley Pty Ltd), Iwatani, Marubeni, Sumitomo, and AGL.

Figure 4.5: Structure of Technology Pilot Demonstration in Australia

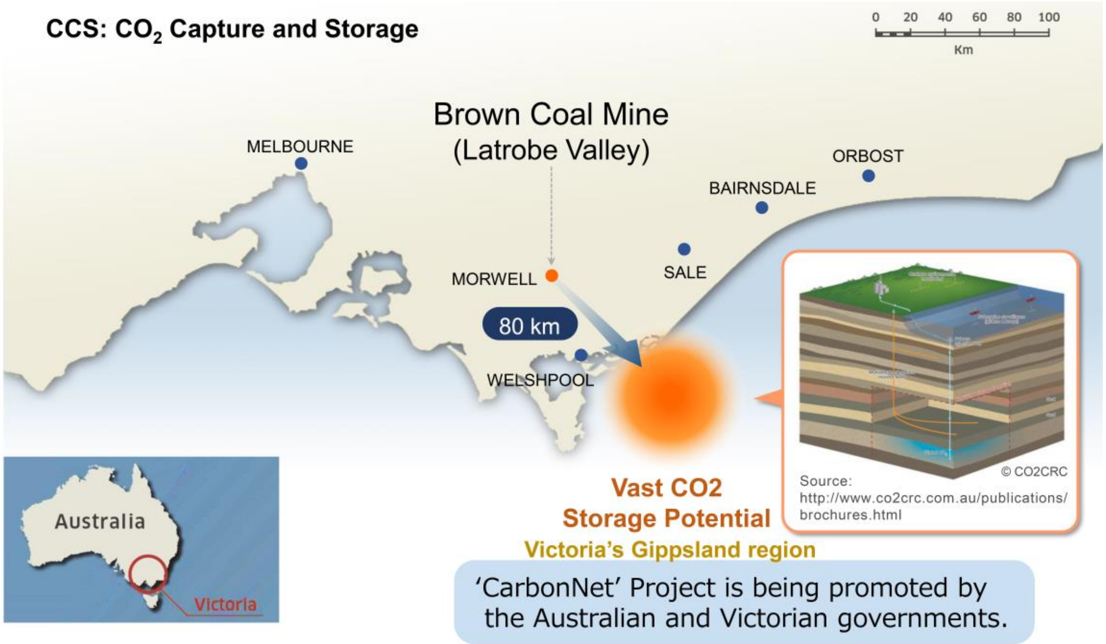


Source: Author.

CCS is an extremely important technology in producing CO_2-free hydrogen. By-produced CO_2 must be captured and sequestered into the aquifer or depleted gas and oil fields under the seafloor. Australia is one of the most advanced countries in terms of CCS (Figure 4.6).

CarbonNet, the famous CCS project, has been promoted jointly by the Australia federal and Victoria state governments. Our project is collaborating with this CarbonNet project.

Figure 4.6: Location of Hydrogen Gas Production Plant and CCS



CCS = carbon dioxide capture and storage.
Source: Author.

3.2. Explanation of each process

3.2.1. Brown Coal (Feed)

Brown coal is an abundant unused resource lying under the earth's surface. However, it contains a large amount of moisture, around 50% water and volatile matter. It easily ignites when dried.

Unlike usual coal, brown coal is difficult to use at a remote place, resulting in its cheaper price; it is also not internationally traded. Additionally, we recognise that hydrogen production using brown coal is one of the most reasonable production methods.

As shown in Figure 4.7, Latrobe Valley, Australia has a huge amount of brown coal. Brown coal layer spreads to the horizon. One-layer thickness is up to 250 metres below the surface. The hydrogen produced from all brown coal in Latrobe Valley is equivalent to Japan's total electrical energy generation for 240 years.

Figure 4.7: Brown Coal Mine

3.2.2. Hydrogen Production Plant for Brown Coal

A. Gasification facility

Brown coal gasification to produce hydrogen will take place at the AGL Loy Yang Complex in the Latrobe Valley. The coal is reacted with oxygen under high pressure and temperature to produce a syngas that consists of carbon monoxide and hydrogen mainly.

During gas purification, the carbon monoxide (CO) is converted to CO_2 using steam, and the hydrogen is separated. In this project, we selected an entrained bed gasification that has a high energy efficiency, has a lot of commercial results, and can easily increase its capacity.

Brown coal has high moisture content and unstable qualities. Therefore, the gasification process needs to resolve various technological hurdles to realise mass production in the future (Figure 4.8).

B. Gas purification facility

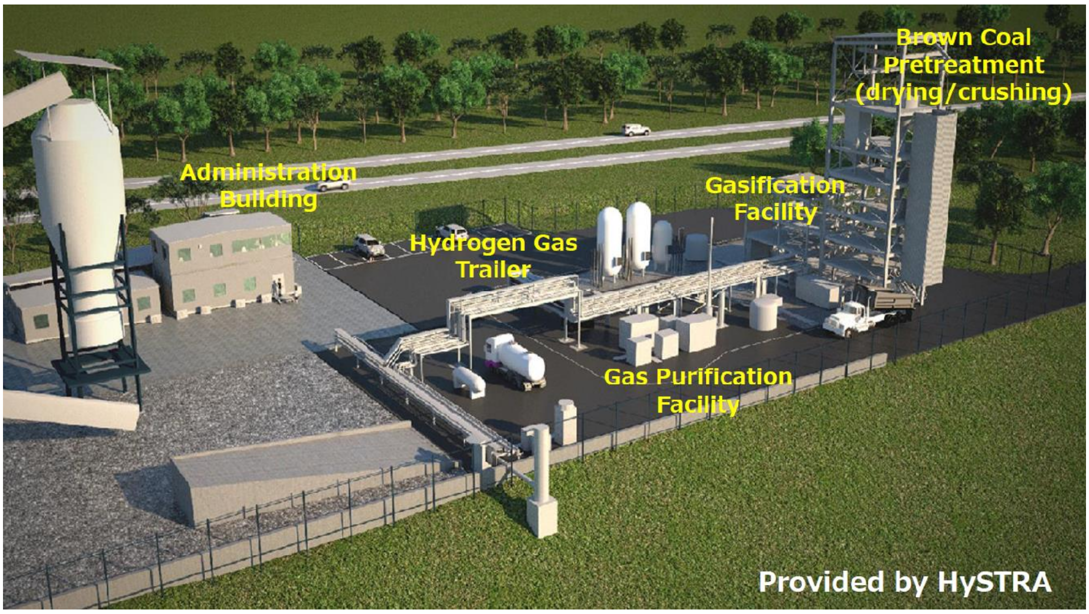
The gas purification facility has two types of treatments on the synthesis gas containing hydrogen, CO, CO_2, and water as the main components, which are produced in the brown coal gasification furnace in the upstream process.

One is a process of increasing the concentration of hydrogen in the synthesis gas by converting CO in the synthesis gas into CO_2 by a water gas shift reaction.

The second is a process in which hydrogen and CO_2 are separated and recovered from the product gas after the shift reaction, and hydrogen is transferred to a hydrogen liquefaction process via a hydrogen pipeline and CO_2 is transferred to a storage process (CarbonNet) via a pipeline.

During extraction of hydrogen from the product gas, it is possible to separate and capture CO_2. This will reduce greenhouse gas (GHG) emissions, despite the energy being derived from fossil fuels.

Figure 4.8: Hydrogen Production Plant for Brown Coal (Latrobe Valley/Image CG Diagram)



3.2.3. Liquefaction/Loading Facility

There are several carriers to efficiently transport the produced hydrogen, such as compressed gas, organic hydride, ammonia, or methane. In this project, we decided that mass transport by liquefied hydrogen has the most potential in decreasing CO_2 emission and, thus, adopt it.

Cooling hydrogen to –253℃ or below turns it from gaseous to liquid state and reduces its volume by 1/800. Such reduction in volume allows for more efficient transport and distribution of more hydrogen.

Kawasaki has already succeeded, and is the first Japanese company, to develop the liquefier in its factory (Figure 4.9).

Kawasaki needs high machinery technology to develop the expansion turbines to keep super high-speed rotation (>100,000 rpm) stable. Kawasaki can diversify this technology from the motorcycle super charger system and the gas turbine system.

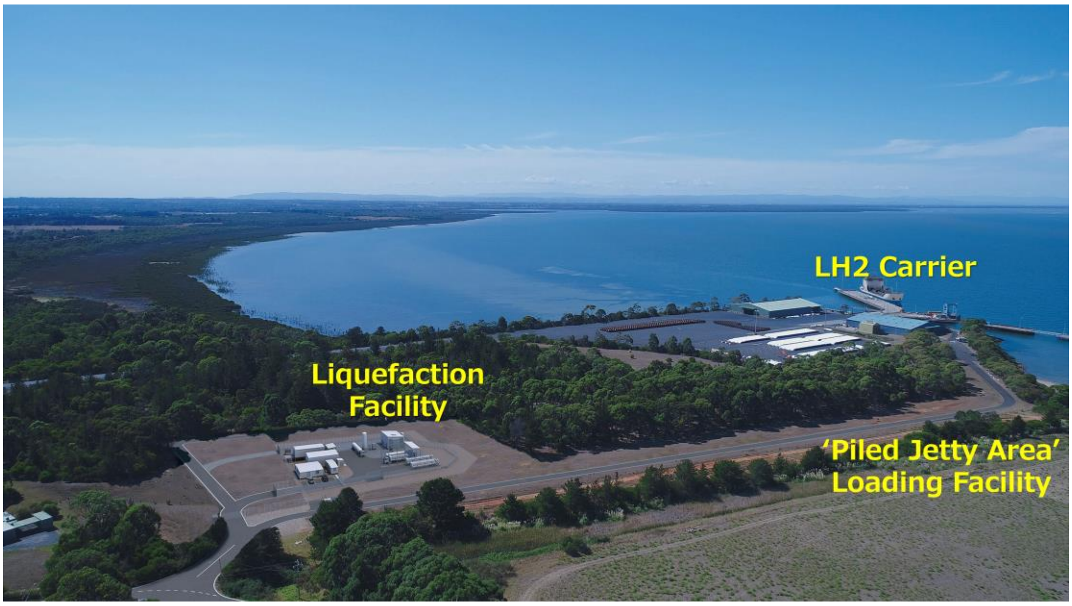
There are many large-scale and high-efficiency facilities in the natural gas liquefaction field. However, the capacity of the hydrogen liquefaction plant is about 5–30 tonnes per day, and the issue is to increase the capacity and improve efficiency.

As shown in Figures 4.10, 4.11, and 4.12, we are constructing a hydrogen liquefaction/loading base in Hastings to be completed in FY2020.

Figure 4.9: Hydrogen Liquefaction Plant in the Harima Factory

Source: Author.

Figure 4.10: Hydrogen Liquefaction/Loading Facility (Hastings/Image CG Diagram)



Source: Author.

Figure 4.11: Overview of Hydrogen Liquefaction/Loading Base Construction (Hastings) in April 2020

Note: The final stage of construction work was aimed to be completed in autumn 2020 and demonstration operation in the second half of FY2020.
Source: Author.

Figure 4.12: Status of Hydrogen Liquefaction/Loading Base Construction (Hastings/Photo) in February 2020

Note: Tree felling and levelling in the main area of the base started on 6 June 2019; underground pipe laying and foundation work are currently under way.
Source: Author.

3.2.4. Liquefied Hydrogen Carrier Ship

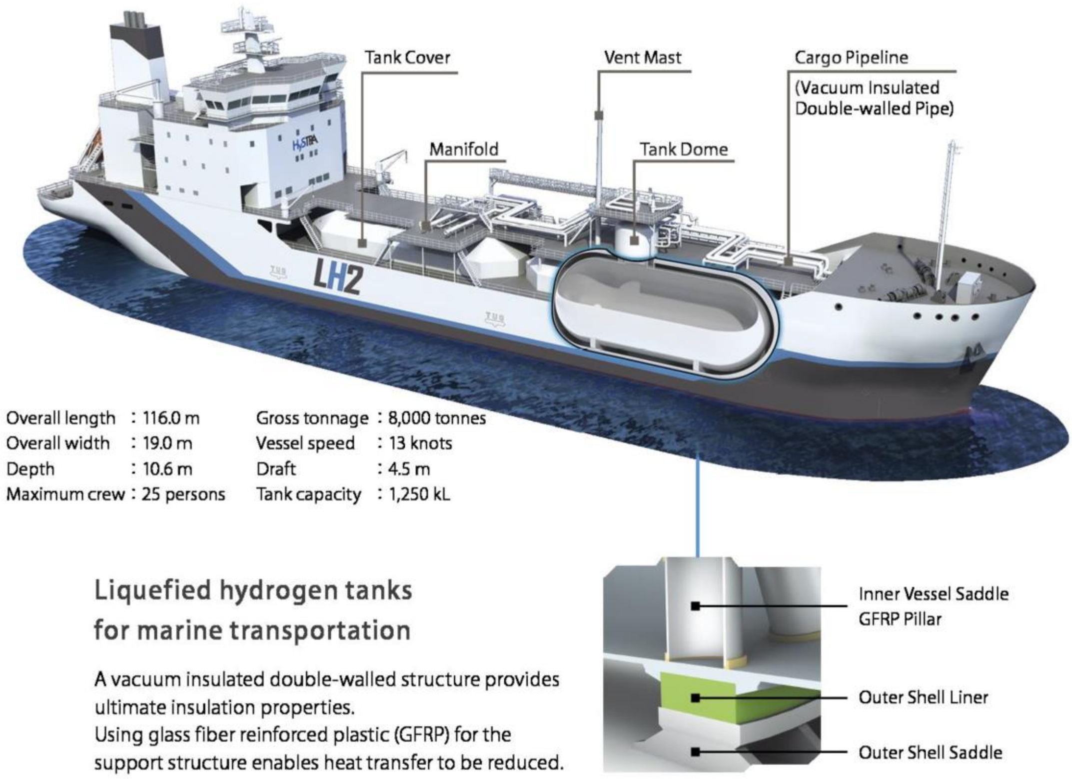
The liquefied hydrogen carrier ship transports produced and liquefied hydrogen by sea from a resource country to Japan, which is a consuming country. Liquefied hydrogen is very convenient for transporting large amounts of hydrogen. Through proven technologies to construct LNG marine carriers, transport by land, and store liquefied hydrogen, Kawasaki developed a new cargo containment system with cryogenic technology to transport liquefied hydrogen in a marine carrier.

Up to now, the operational performance of large liquefied hydrogen transport tanks is unprecedented in the world. For the first time, Kawasaki succeeded in having the International Maritime Organization Maritime Safety Committee approve and recommend the offshore carriage of liquefied hydrogen in bulk.

Figure 4.13 shows a liquefied hydrogen carrier ship now being constructed for pilot demonstration. Installed is a 1,250 m^3 liquefied hydrogen storage tank. Liquefied hydrogen loading weight is 75 tonnes at one time.

This time Kawasaki adapted the proven electric propulsion system using the diesel generator to focus on the demonstration of cargo containment system for liquefied hydrogen. Kawasaki plans to use boil-off gas (BOG) as a propulsion fuel at the start of commercial operation. This utilisation BOG system is adapted to the LNG carrier ship and can contribute to decreased CO_2 emission for marine transport when adapted to the LH2 carrier ship.

Figure 4.13: Outline of Pilot LH2 Carrier Ship



Source: HySTRA.

Kawasaki launched the ship on 11 December 2019 at the Kobe Factory, one of its shipbuilding yards in Japan (Figure 4.14). The ship, called the Suiso Frontier, is owned by CO_2-free Hydrogen Energy Supply-Chain Technology Research Association (HySTRA).

Kawasaki will finish the outfitting of a liquefied hydrogen carrier ship by mid-2020. During commercialisation, Kawasaki is planning to ship 160,000 m^3 liquefied hydrogen, just like an LNG ship, around 10,000 tonnes at a time.

Figure 4.14: Pilot LH2 Carrier, Cargo Containment System Construction Status (Kawasaki Factory)

Source: Author.

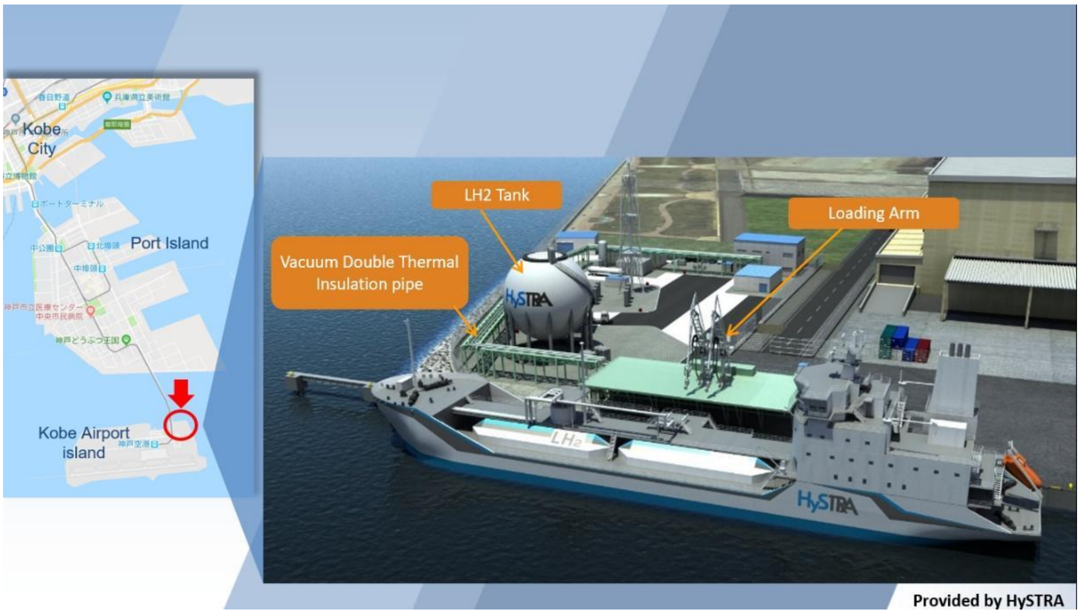
3.2.5. Storage and Unloading Facility

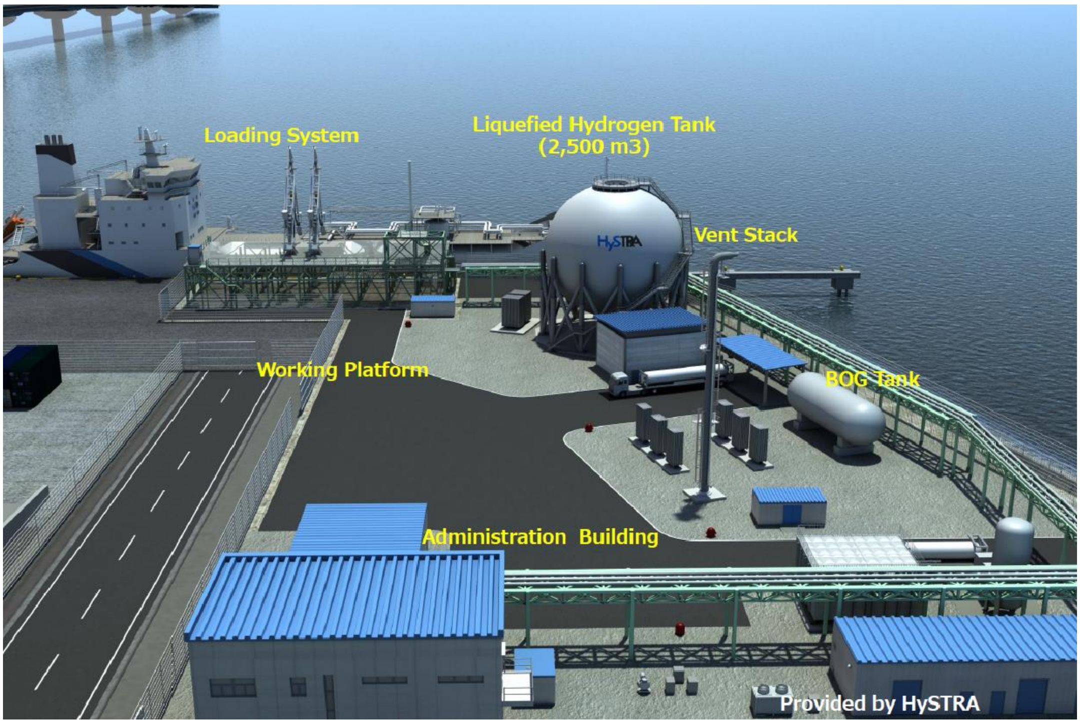
The liquefied hydrogen carrier arrives at the unloading terminal after a journey of around 9,000 km. A loading arm system unloads the hydrogen from the carrier ship into an on-land liquefied hydrogen storage tank, whilst maintaining a temperature of –253℃.

This is the first new energy terminal in Japan. This liquefied hydrogen cargo terminal will be installed in Kobe Airport Island (Figures 4.15 and 4.16).

There, several equipment and facilities such as a liquefied hydrogen tank (2,500 m^3), unloading system for liquefied hydrogen, BOG holder, and others are being constructed. All are cutting-edge facilities and will be completed by 2020.

Figure 4.15: Liquefied Hydrogen Cargo Loading Base in Kobe Airport Island (CG View)





BOG = boil off-gas.

Figure 4.16: Status of Construction of LH2 Cargo Loading Base (Kobe Airport Island) in April 2020

Note: The final stage of construction is targeted to be completed in summer 2020 and demonstration operation in the second half of FY2020.

4. Estimating Hydrogen Cost

This section presents a cost (CIF base) analysis on liquefied hydrogen energy carrier supply chain. This analysis roughly estimates hydrogen cost in the international supply chain from a foreign country (Australia) to Japan by ship. We calculated hydrogen supply cost per 1 normal cubic metre in 2030 and further into the future.

This analysis is not a forecast but just a cost study using data in 2011 because we did not consider future expected data, such as inflation, discount rate, and exchange rate fluctuation.

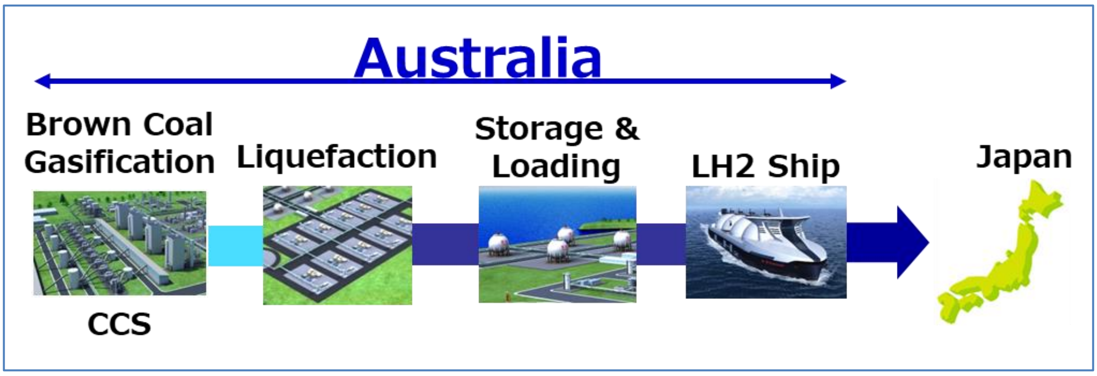
For 2030, the cost, capacity, and efficiency of each facility, which includes technological advancement to 2030, are summed up.

In the case of the further future, the cost, capacity, and efficiency of facilities are assumed with reference to the correlation between demand and cost in the LNG market.

4.1. Scope of the cost study

The target scope of this cost analysis is shown in Figure 4.17. Included in the target scope are the following: (i) brown coal (feed); (ii) hydrogen production facilities (pretreatment, gasification, and purification); (iii) CCS; (iv) transport from the hydrogen gas production site to the liquefied hydrogen base; (v) hydrogen liquefaction facility; (vi) loading terminal; (vii) sea transport; and (viii) storage and unloading facility.

Figure 4.17: Target Scope of the Cost Analysis in Liquefied Hydrogen Supply Chain



Source: Author.

4.2. Specification of each process of the liquefied hydrogen supply chain

Table 4.1 shows the specification of each process due to estimated hydrogen cost.

Table 4.1: Specification of Each Process of the Liquefied Hydrogen Supply Chain

Process	Specification (770 t/d)
Gas production	Fluidised bed gasification type Desulphurisation and decarboxylation: Selexol method Amount of brown coal supply: 540 tonne/h
Gas purification	Pressure swing adsorption (PSA) type Purity 99.999%
Liquefier	Capacity 50 t/(d unit) 20 units Power consumption 6.17 kWh/kg-H2
Loading terminal	200,000 m^3 (50,000 m3/tank, 4 tanks)
LH2 cargo ship transport	160,000 m^3/ship, 2 ships Velocity 16 knots (29.7 km/h)

Source: NEDO (2012), Author.

4.3. Estimation of hydrogen cost in 2030

4.3.1. Precondition for Hydrogen Cost Calculation in 2030

Table 4.2 shows the precondition for hydrogen cost calculation in 2030. These cost estimations were conducted in 2011, and the conditions used for the estimation are as of 2011.

(a)–(g) Setting condition

It is assumed that the year to start a large commercial supply chain will be 2030, and that a large amount of Australian brown coal–derived liquefied hydrogen will be imported to Japan.

<Precondition for sea transportation>

Route: Victoria, Australia to Japan, Cruise distance: Approx. 9,000 km

Ship velocity: 16 knots (29.7 km/h), Annual working days: Approx. 330 days

Loading days: 4 days (total unloading/loading), Annual load: 238,500 t-H2/year.

Annual number of round trips: Approximately 22 times

(h) Project period

The project period is 30 years. However, since the continuation or termination of the business after 30 years has not been decided at this time, dismantling and removal cost will not be included.

(i)–(k) Depreciation years, depreciation methods, tax rates

Since the hydrogen chain model operator will be an Australian corporation, it will be subject to Australian tax laws. A 15-year depreciation and fixed rate depreciation will be adopted, which can reduce the tax cost at the beginning of the year. The tax rate used in Australia is 30%.

(l) Investment and debt ratio

Finance usually involves a sufficient amount of investment to be screened before it is screened. According to information from the Japan Bank for International Corporation (JBIC), a group of Japanese policy-based financial institutions, JBIC's financial debt ratio is mostly 50% which we adapted.

(m) Borrowing rate

Since the US 6-month LIBOR (London Inter-Bank Offered Rate) average over the past 5 years is 2.66%, the JBIC US currency borrowing is estimated to be 0.25 (bank fee) + 2.66 = 2.9%. The economy will be examined at a borrowing interest rate of 3%, considering the accuracy of the economic examination of the commercial chain at present.

(n) Subsidy ratio

The subsidy ratio will be 0% in order to study the economic efficiency of the project.

(o)–(s) Main unit price

Since this study aims at CO_2-free hydrogen production, the cost of CO_2 storage is included in the cost. For electricity used in this project, the unit price of CO_2-free electricity is set based on the use of renewable energy or fossil fuel + CCS.

Table 4.2: Precondition for Hydrogen Cost Calculation in 2030

Items		Description	
(a)	Use technology	Large commercial supply chain	
(b)	Hydrogen production location	Australia (9,000 km)	
(c)	Hydrogen production method	Brown coal gasification hydrogen production	
(d)	Hydrogen production amount	770 tonnes per day	
(e)	CO_2 capture and storage (CCS)	Implemented CCS in collaboration with CarbonNet Project	
(f)	Annual unloading amount in Japan	225,540 tonnes per year	Annual operating rate of H2 production facility is 89%
(g)	Annual number of round trips	22 times	
(h)	Project period	30 years	
(i)	Borrowing period	15 years	
(j)	Years of depreciation*	15 years	
(k)	Tax	30%	
(l)	Investment and debt ratio	50:50	
(m)	Borrowing rate	3% per year	
(n)	Subsidy ratio	0%	
(o)	Brown coal Cost	A$15 per tonne	Shipping fee included
(p)	Electrical	A$70 per MWh	Electricity by renewable energy
(q)	Water	A$2 per tonne	
(r)	CO_2 treatment	A$15 per tonne	CarbonNet storage cost
(s)	Exchange rate	¥81/A$ €0.61/A$ US$0.73/A$	Average rates from 1991 to 2010

Note: Depreciation costs are calculated using the declining balance method. Hydrogen price is necessary for profit and tax calculation, but here hydrogen cost and hydrogen price are the same.
Source: NEDO (2012), Author.

4.3.2. Capital Expenditure (CAPEX)

As a result of calculating the cost of each facility listed in Table 4.1, CAPEX totalled ¥750 billion.

The cost of each facility includes equipment costs, civil engineering, electricity, machinery, construction/installation costs, land costs equivalent to the total installation area calculated from the layout plan, and site infrastructure costs such as roads and management facility.

Miscellaneous expenses include licences for plant installation, legal compliance, and various expenses related to finance.

The cost of constructing a new power line for a hydrogen liquefaction plant installed at the hydrogen loading terminal is not included in this project, assuming it will be shared with other facilities.

As for port facilities, the equipment required for the hydrogen loading terminal is included in the equipment cost. However, the construction, dredging, and pier construction costs are not included in the equipment cost borne by this project. The hydrogen production facility and hydrogen liquefaction facility accounted for a large proportion of the facility cost.

4.3.3. Operating Expense (OPEX)

The total operating cost for brown coal (raw material), electricity, water/nitrogen, CCS, maintenance, and labour was about A$45 billion. A fluidised bed gasifier with the lowest overhead costs and low CO_2 emissions was adopted.

Electricity accounted for the largest portion of the operating cost, and decreased electricity consumption is the most important factor in reducing hydrogen cost. Particularly for the hydrogen liquefaction facility, the proportion of power consumption is large. To reduce the operating costs, it is important to improve the performance of the hydrogen liquefaction facility and the gas production facility, such as air separation equipment.

4.3.4. Hydrogen Cost Calculation Formula

The hydrogen production cost (hereinafter, hydrogen cost) was calculated from the equipment cost and annual cost.

Hydrogen cost is defined as follows and indicates the average cost during the project period.

$$Hydrogen\,Cost = \frac{\{CAPEX + \sum(Interest + Tax)\} \,/\, ProjectYears + OPEX}{H2\ Annual\ Production}$$

where

Hydrogen Cost : Hydrogen cost (¥/Nm3)
CAPEX : Equipment cost (¥)
Σ (Interest + Tax) : Interest payment and total tax during the project period (¥)
ProjectYears : Project years (years)
OPEX : Annual expenses (¥/year)
H2 Annual Production : Annual hydrogen production (Nm3 CIF/year)

Interest payment will be as follows if the principal repayment is

$$\sum(Interest) = \sum_{i=1}^{DebtYears}\{CAPEX \times Debt\ Ratio - DebtPayment \times (i-1)\} \times ir$$

where

Debt Ratio	: Debt ratio (decimal)
DebtYears	: Debt years (years)
DebtPayment	: Repayment of principal (¥/year)
ir	: Interest rate (decimal)

Taxes can be calculated by multiplying profits by tax rates.

$$Income = H2\ Annual\ Production \times HydrogenPrice - (OPEX + Interest) - Depreciation$$

$$\mathrm{T}ax = Income \times Tax\ Rate$$

where,

Income	: (¥/y)
HydrogenPrice	: (¥/Nm3)
Depreciation	: (¥/y)
Tax Rate	: Decimal

Amortisation is calculated using the declining balance method. Hydrogen prices are required for profit and tax calculations. However, here hydrogen costs and hydrogen prices are assumed to be the same.

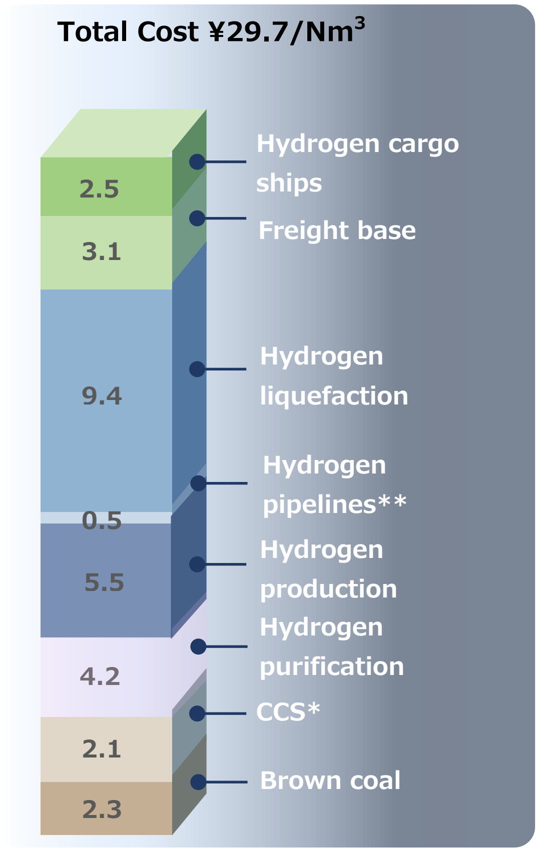
4.3.5. Calculation Result of Hydrogen Cost (¥/Nm^3) in 2030

The calculation result of hydrogen cost (CIF base) is shown in Figure 4.18. The total cost of liquid hydrogen supply chain under the above precondition is ¥29.7 /Nm^3.

Hydrogen liquefaction cost is the highest ratio (¥9.4/Nm^3 (31.6%). Subsequently, hydrogen production cost (¥5.5/Nm^3, 18.5%) and hydrogen purification cost (¥4.2/Nm^3, 14.1%) are high ratios. On the contrary, the ratio of hydrogen cargo ships (¥2.5/Nm^3, 8.4%) and CCS (¥2.1/Nm^3, 7.1%) to the total cost is relatively low.

To reduce the hydrogen cost, it is essential to reduce the costs of the hydrogen production and liquefaction facilities, which account for a large proportion of CAPEX. In OPEX, improvement of liquefaction efficiency is also an important issue. It is also important to reduce costs by increasing the scale-up of facilities.

Figure 4.18: Result of Cost Analysis (CIF Base) in Liquefied Hydrogen Supply Chain



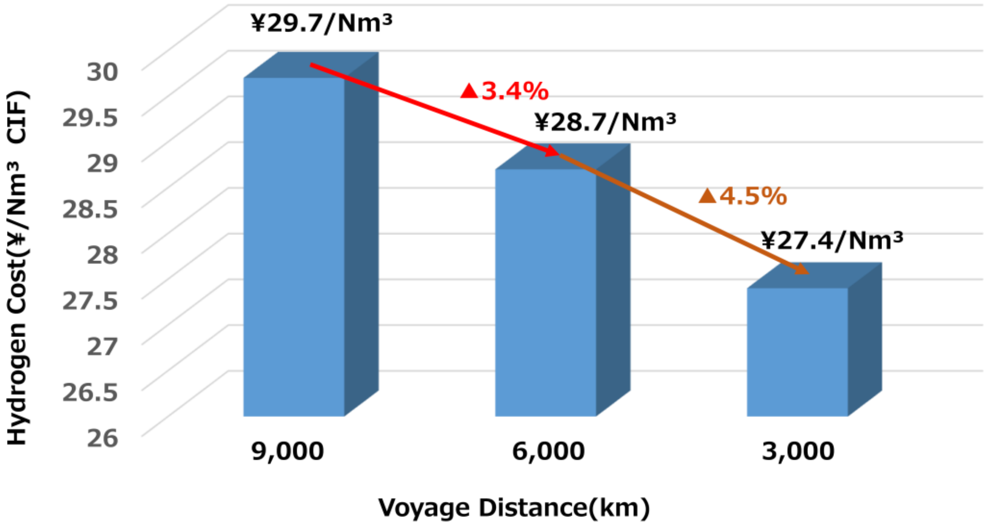
Source: NEDO(2012), Author.
* The CCS cost is the amount presented by the CarbonNet Project.
** Pipeline cost includes expenses related to plant installation licences, legal compliance, and finance.

4.3.6. Analysis on Hydrogen Transport Costs by Voyage Distance

A sensitivity analysis of hydrogen cost by voyage distance was conducted. The set voyage distances are short distance (3,000 km), medium distance (6,000 km), and long distance (9,000 km), and the hydrogen cost is calculated for each voyage distance. The effect of voyage distance on hydrogen cost is shown in Figure 4.19.

The result shows that the hydrogen cost can be reduced by ¥0.3–¥0.4/1,000 km. The reason for the reduction in hydrogen cost is thought to be that the number of voyages increases due to the short distance. If hydrogen production from renewable energy becomes more popular in the future, Southeast Asia and China are expected to be promising manufacturing locations.

Figure 4.19: Effect of Voyage Distance on Hydrogen Cost



Source: Author.

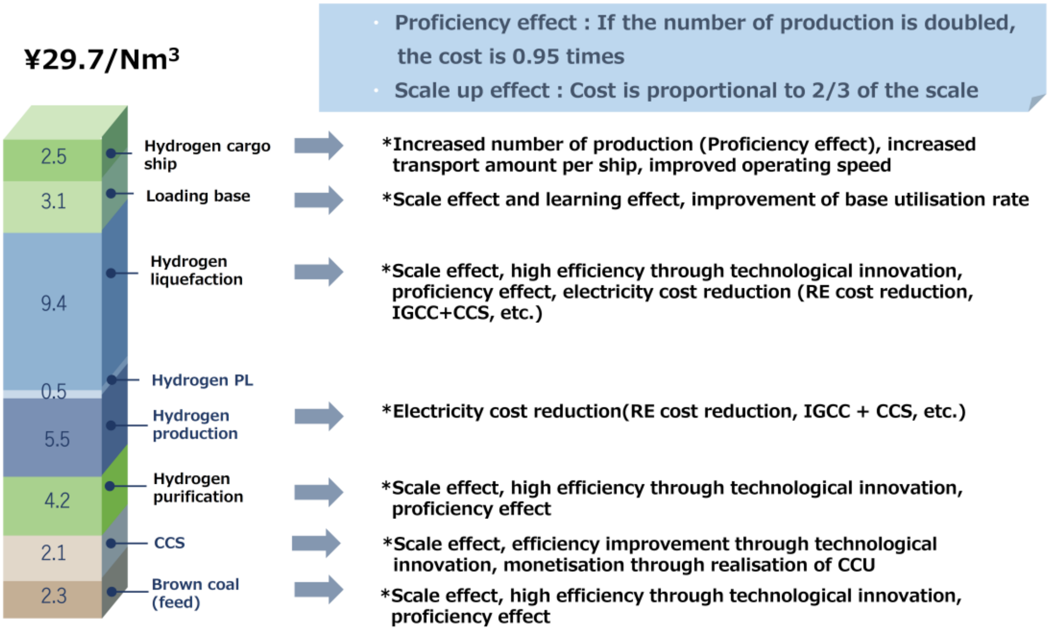
4.4. Estimation of hydrogen cost in the further future

4.4.1. Possibility of Further Hydrogen Cost Reduction in the Future

In the previous calculation, the hydrogen cost in the liquefied hydrogen supply chain is estimated to be ¥29.7/Nm^3 at the early stage of commercialisation in 2030. This section studies the reduction of hydrogen cost due to the possibility of further decreased hydrogen cost in the further future (say, in the 2050s).

Figure 4.20 shows the possibility of further hydrogen cost reduction in each process. Overall, the effect of proficiency in each process and decrease in electricity cost by renewable energy contributes to reduced hydrogen cost. It will also greatly contribute to reduced hydrogen cost. In addition, both the increase in the number of voyages and the improvement in operating rate will contribute to reduced hydrogen cost in CAPEX and OPEX.

Figure 4.20: Possibility of Further Reduction of Hydrogen Cost Co

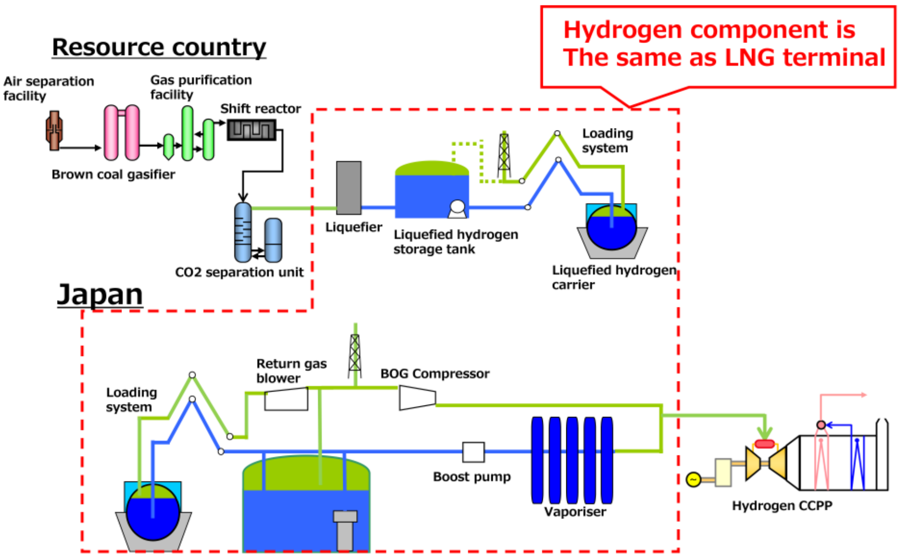


Source: Author.

4.4.2. The History of the LNG Supply Chain Cost

Figure 4.21 shows the similarity of the liquefied hydrogen supply chain process to the LNG process. Thus, we believe that future hydrogen cost will be reduced in the same way as LNG cost. In this section, we researched the past LNG demand and cost changes to consider future hydrogen cost reductions.

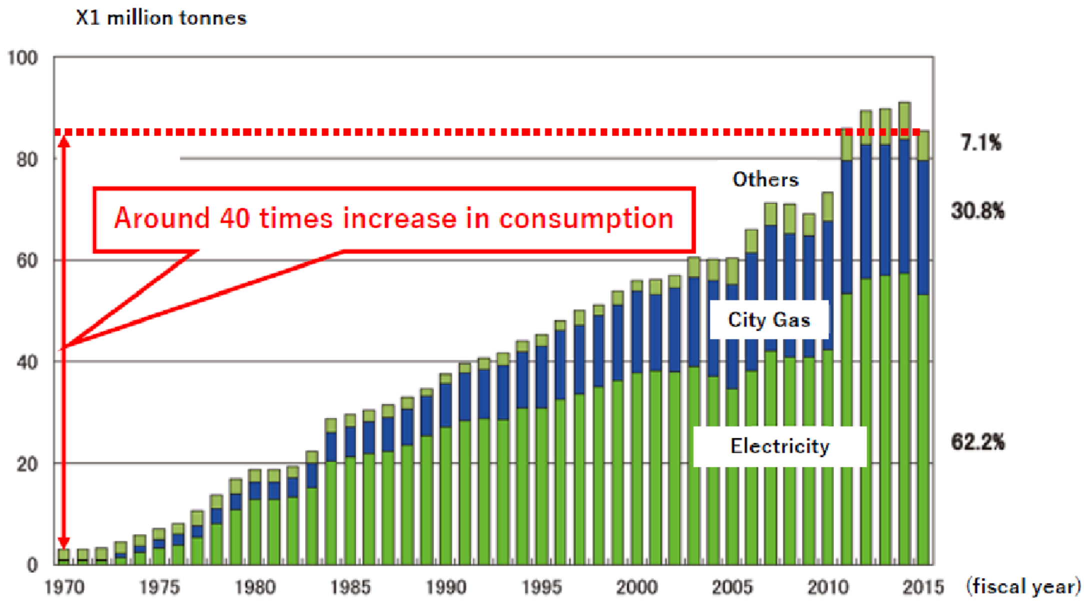
Figure 4.21: Liquefied Hydrogen Supply Chain System Produced from Brown Coal



CCPP = combined cycle power plant, LNG = Liquefied natural gas.
Source: Author.

Figure 4.22 shows the changes in Japan's domestic consumption of natural gas. During the 35 years from 1969 (2,233 tonnes/y) to 2015 (85,553 tonnes/y), the consumption of natural gas has increased about 40 times (METI–ANRE, 2016). Natural gas consumption is increasing rapidly.

Figure 4.22: Changes in Japan's Domestic Consumption of Natural Gas



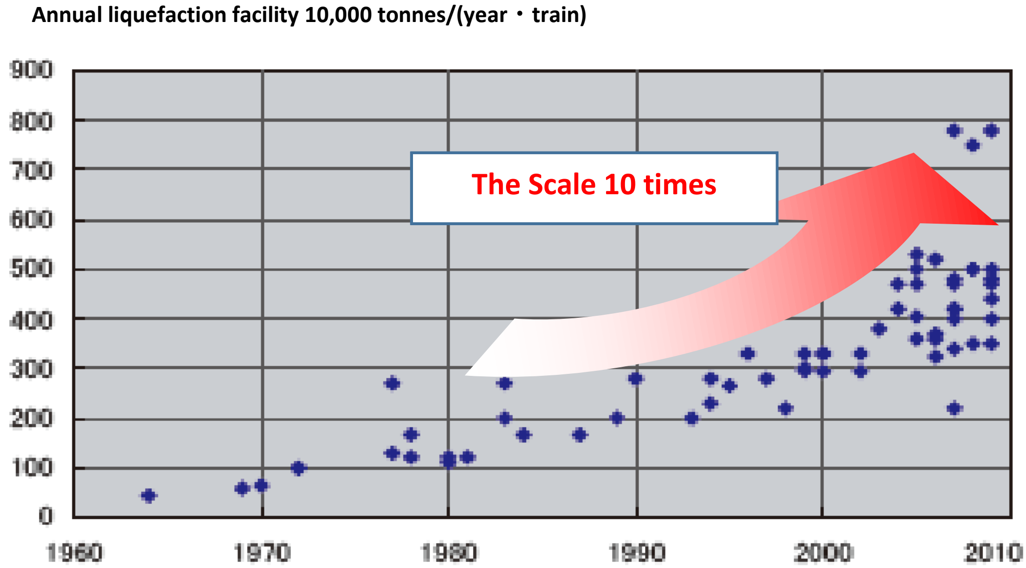
Source: METI–ANRE (2016).

Figure 4.23 shows the capacity and cost changes of an LNG liquefaction facility (Miyazaki, 2005). When Japan first imported LNG in 1960, the liquefaction capacity was around 500,000 tonnes-LNG/year. Forty years later, in the 2000s, the scale expanded about 10 times due to the increase in demand (5–7 million tonnes-LNG/year. Meanwhile, the cost of the LNG liquefaction facility has been halved in about 40 years.

This was when the scale of liquefaction capacity increased 10 times. LNG cost was halved due to technological progress and expansion of LNG-related facility. As mentioned in section 4.4.4.1, cost reduction was the effect of proficiency level and demand for mass transportation, high efficiency of facility, etc.

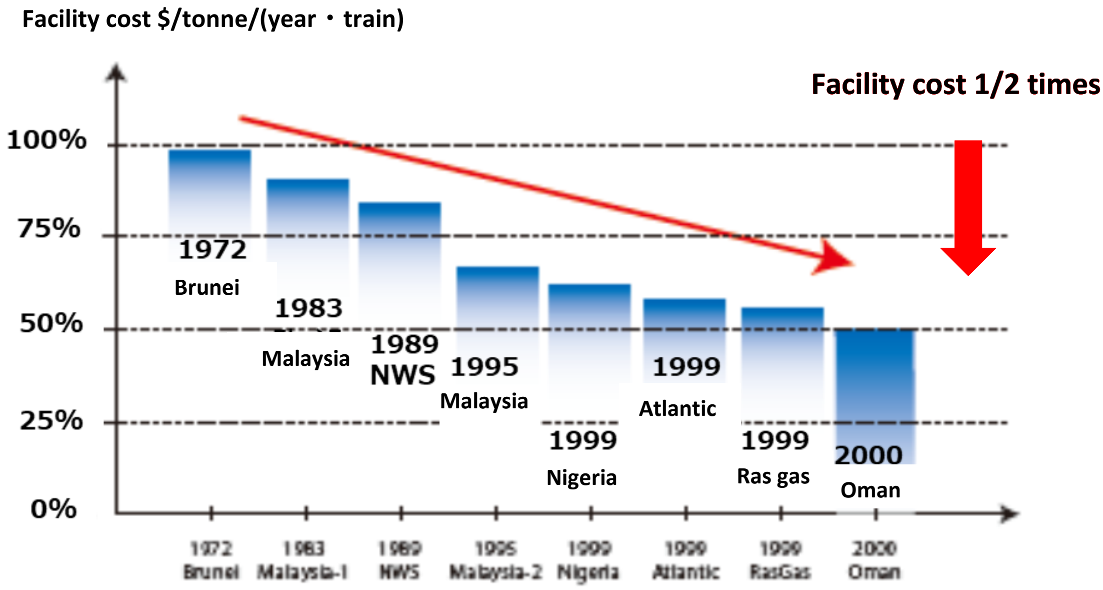
Figure 4.23: Capacity and Cost Changes in LNG Liquefaction Facility

a) Annual change of liquefaction capacity



Source: Miyazaki (2005).

b) Annual change of the cost of liquefaction facility



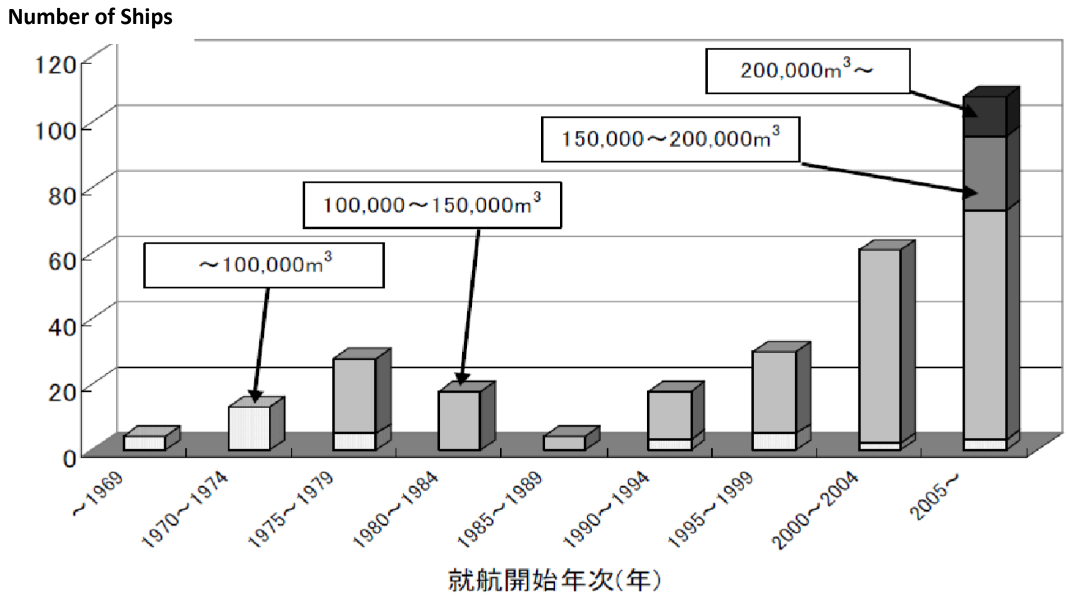
Source: Miyazaki (2005).

Figure 4.24 shows the cost changes of LNG facilities (LNG tankers) (JBIC, 2006). In the 1960s, LNG tankers with a capacity of 100,000 m^3 or less were the mainstream. With the expansion and spread of demand, LNG tankers with a capacity of 150,000 m^3 or more were constructed and have been the mainstream since the 2000s.

On the other hand, the cost of an LNG tanker was US$280 million in the early 1990s. It decreased to US$140 million to US$200 million in the 2000s, resulting in a 30%–50% cost reduction. To reduce facility costs, LNG cost to Japan decreased by 40%. Please also refer to Appendices 1 and 2 on LNG carrier construction history (Itoyama, 2012).

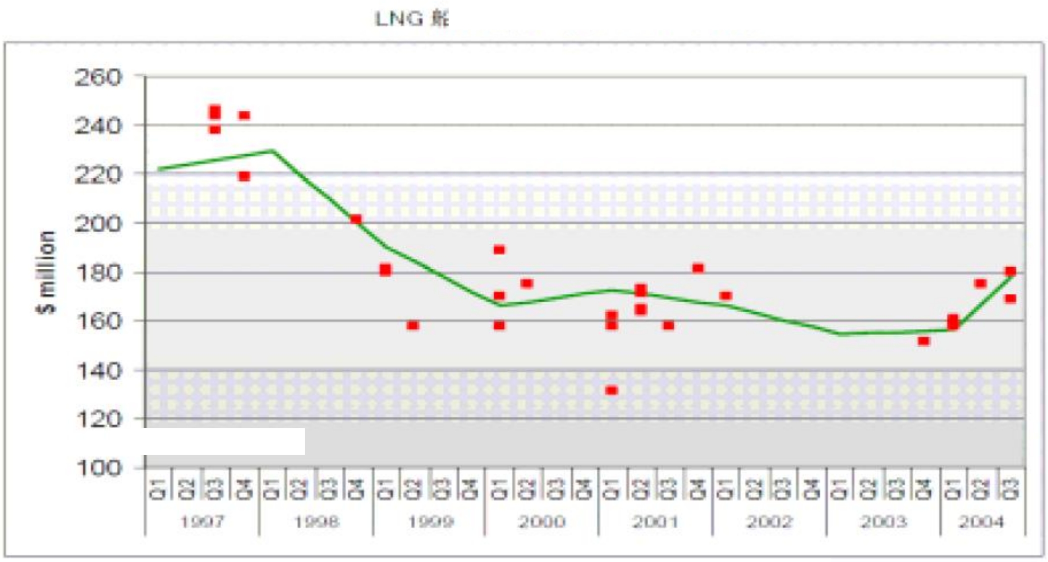
Figure 4.24: Cost Change in LNG Tanker

a) Annual change in the number and capacity of LNG carriers



Source: JBIC (2006).

b) Annual changes in the construction cost of LNG ship (since 1997)



Year of commencement of service

Source: JBIC (2006).

4.4.3. Possibility of Hydrogen Cost Reduction in the Further Future

By applying this relationship between LNG demand and cost reduction, we studied the future reduction of hydrogen cost. As shown in Figure 4.25, if the commercial hydrogen business starts in 2030 and demand increases in the 2050s, hydrogen costs will be reduced by 40% (around ¥18/Nm^3) of the hydrogen cost in 2030 (¥29.7/Nm^3).

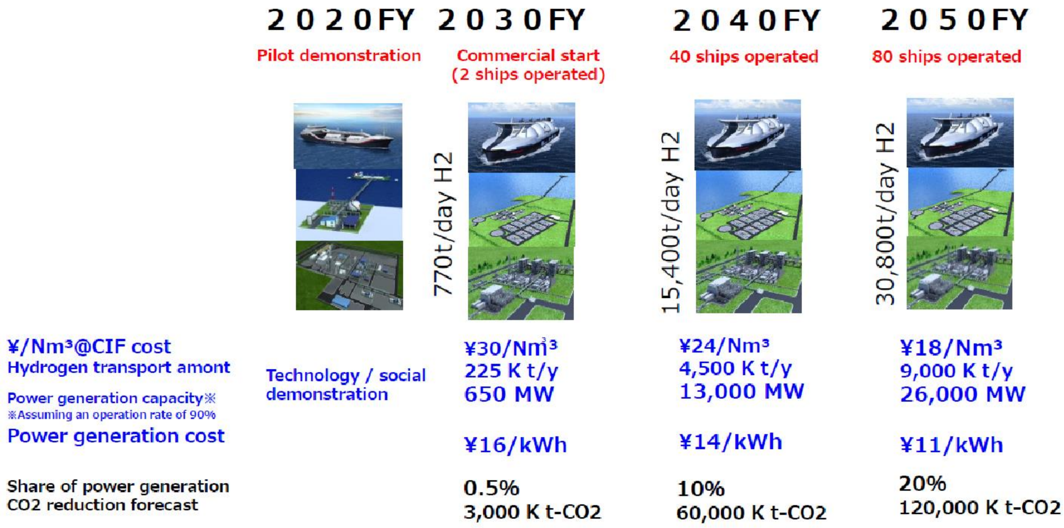
Otherwise, hydrogen transportation can be calculated at 9Mt/y; power generation capacity at 26,000 MW; and power generation unit price at ¥11/kWh). We have not considered carbon pricing or government assistance at this time, so it is highly possible that this cost will be further reduced.

In the 2050s, the prices of other fossil fuels will rise further, resulting in hydrogen production from lignite more competitive. Appropriate overseas bases such as Southeast Asia and China will also produce large amounts of hydrogen using renewable energy.

Hydrogen consumption will also increase. It is highly possible that a full-scale hydrogen society will arrive. If hydrogen will be used to generate commercial power in Japan, it will be more expensive than fossil fuel in 2030. However, the cost of CO_2-free power generation produced by brown coal is expected to be cheaper than the same one produced by renewable energy, such as wind power and solar power.

In the future, when commercialisation will be widely advanced, the cost of hydrogen power generation can be competitive enough with fossil fuel power generation. Regarding CO_2 emission, 120 Mt of CO_2 is also expected to be reduced, greatly contributing to the measures against global warming.

Figure 4.25: Estimation of Hydrogen Costs in Further Future



Source: Author.

5. Conclusion

Chapter 4 reviewed and examined liquefied hydrogen supply chain for decarbonisation, provided an overview of liquefied hydrogen energy supply chain pilot project between Australia and Japan, and forecasted future hydrogen cost. The findings are as follows:

5.1. Liquefied hydrogen supply chain for decarbonisation

- Liquefied hydrogen supply chain is important for the government-proposed basic energy strategy.
- Hydrogen does not emit CO_2 during combustion and is environment friendly.
- The spread of the liquefied hydrogen supply chain is extremely beneficial for environmental measures.
- Liquefied hydrogen is 1/800 of the volume of gaseous state. The transport of liquefied hydrogen can be efficient for large amounts of hydrogen.
- Liquefied hydrogen is non-toxic and can be used simply by evaporating it, without adding extra energy.
- In the life-cycle analysis (LCA), liquid hydrogen supply chain produced from brown coal with CCS is comparable to high-pressure hydrogen supply chain produced from renewable energy.

5.2. Overview of hydrogen energy supply chain pilot project between Australia and Japan

- Brown coal is gasified and refined using an oxygen-blown gas furnace on the coal mine side. The refined hydrogen gas is transported to the port side by pipeline, and then liquefied at the loading terminal on the port side. The process of storing and transporting to Japan by a liquefied hydrogen carrier ship was selected as the optimum process.
- The Australia–Japan Liquefied Hydrogen Supply Chain Pilot Demonstration Project, targeted for FY2020, is under way.
- This project aims to confirm that liquefied hydrogen can be safely and efficiently shipped for over 9,000 km.

5.3. Study of future hydrogen cost

- Aimed to be commercialised in 2030, total hydrogen imports were estimated to be 225,540 tonnes/year.
- The hydrogen cost (CIF [cost, insurance, and freight] price) was calculated in case. Australian brown coal is gasified to produce hydrogen, which is a clean fuel and used in Japan. Sensitivity analysis and examination of diffusion potential of each factor were conducted.
- At the same time, regarding changes in LNG demand and costs in similar supply chains, we assumed hydrogen demand, costs, and CO_2 reductions for the time the commercialisation of hydrogen supply chains will expand after 2030.
- The estimated hydrogen cost (CIF base) in 2030 is ¥29.7/Nm^3.
- Amongst hydrogen costs, the ratio of hydrogen liquefaction（¥9.4/Nm^3, 31.6%) was the highest, followed by hydrogen production（¥5.5/Nm^3, 18.5%）, and hydrogen purification（¥4.2/Nm^3, 14.1%). The cost reduction of these three devices will be essential in the future.
- The factor analysis of cost reduction in the further future revealed that the large size of each equipment, improved performance, and high efficiency are essential.
- According to our study, in the further future, the amount of hydrogen import will be 9 Mt/y; hydrogen CIF cost, ¥18/Nm^3; power generation capacity, 26,000 MW; power generation cost, ¥11/kWh; and amount of CO_2 reduction, 120 Mt/y.

Thus, the result of the analysis confirms that the future proposed energy system on the liquefied hydrogen supply chain model using hydrogen, which is a carbon-free clean fuel, is highly feasible both technically and economically.

With the aim of starting, we will conduct a technical and safety demonstration in the pilot chain, targeting a commercialisation demonstration in 2025, and another in 2030.