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Demand and Supply Potential of Hydrogen Energy in East Asia – Phase 3

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Demand and Supply Potential of Hydrogen Energy in East Asia – Phase 3

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Preface

Decarbonisation means targeting zero net emissions of carbon dioxide (CO_2) and follows the trend of new low-carbon energy technologies that will be widely available around 2040–2050. These also include carbon capture, utilisation, and storage (CCUS); hydrogen; and ammonia. These technologies are expensive compared to existing low-carbon fuels and technologies available in the East Asia Summit (EAS) region, such as natural gas and solar photovoltaic (PV) systems. However, CCUS, hydrogen, and ammonia are expected to become affordable around 2040–2050 due to innovation and technology development as well as market growth.

Hydrogen production is based on fossil fuels, such as coal and natural gas, using CCUS and water electrolysis technology. To produce hydrogen, unused energies should be explored, encompassing hydropower in isolated areas, flared gas at oil and natural gas production sites, and low-ranked coal. CCUS can be applied to flared gas and low-ranked coal, which will not affect existing energy supply due to unused energy.

In the case of transporting hydrogen, various factors must be addressed, including its form, distance, and amount, as hydrogen demand sites are usually not located at production sites. Therefore, an optimal hydrogen transport network is needed to connect these sites, applying hydrogen transport technologies.

The Economic Research Institute for ASEAN and East Asia (ERIA) continues to implement the hydrogen potential study in phase 3. This phase studies how hydrogen can contribute to decarbonisation and be produced from unused energy sources. ERIA also organised the hydrogen working group meetings, which discussed how hydrogen contributes to carbon-neutral targets for several EAS countries.

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This report was developed by a working group consisting of representatives from the Economic Research Institute for ASEAN and East Asia (ERIA); Institute of Energy Economics, Japan (IEEJ); and ASIAM Research Institute, with the support of Chiyoda Corporation and Kawasaki Heavy Industries. The IEEJ team was responsible for forecasting hydrogen production potential. The ASIAM Research Institute team analysed an optimal hydrogen network in the East Asia Summit (EAS) region with support from Chiyoda Corporation and Kawasaki Heavy Industries. The working group also contributed to several successful workshops on carbon neutrality.

On behalf of ERIA, I would like to acknowledge the members of the working group for their effective work and contribution to this successful research study.

Shigeru Kimura
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Abbreviations and Acronyms

ASEAN	Association of Southeast Asian Nations
bcm	billion cubic metre
CCUS	carbon capture, utilisation, and storage
CO_2	carbon dioxide
EAS	East Asia Summit
ERIA	Economic Research Institute for ASEAN and East Asia
FCV	fuel cell vehicle
FH2R	Fukushima Hydrogen Energy Research Field
GCV	gross calorific value
GW	gigawatt
ICE	internal combustion engine
IEEJ	Institute of Energy Economics, Japan
km	kilometre
Lao PDR	Lao People's Democratic Republic
MCH	methylcyclohexane
MW	megawatt
NCV	net calorific value
NEDO	New Energy and Industrial Technology Development Organization
Nm^3	normal cubic metre
PJ	petajoule
PV	photovoltaic
SDS	sustainable development scenario
STEPS	stated policy scenario
US	United States

Executive Summary

Hydrogen is mostly produced from fossil fuels by applying natural gas reforming, low-ranked coal gasification, and water electrolysis using renewable electricity through solar photovoltaic (PV) systems and hydropower plants. Natural gas and coal are still considered important fuels in the East Asia Summit (EAS) region; natural gas is a key transition to reduce carbon dioxide (CO_2) emissions in the EAS region, but coal is still used for power generation in most of Asia. Renewable electricity should be used as a source for industry, commercial, and residential sectors, as it is more efficient than producing hydrogen. Yet, as a first step, it is better if hydrogen is produced by unused or unutilised energies.

There is much flared gas at oil and gas fields, and the waste gas flared can be recovered and used for hydrogen production. In addition, there is abundant low-ranked coal, such as lignite and brown coal, in Asia that cannot be used due to its low quality; production of hydrogen from low-ranked coal is ideal as well. Hydropower potential is great in the Association of Southeast Asian Nations (ASEAN) region, but the locations it can be produced are in isolated areas. In these places, electricity demand is low compared to generation potential, and the cost of constructing long transmission lines between these areas and urban areas is huge – therefore, hydropower plants have never be developed. Hydrogen production from hydropower and its transport to demand areas are, however, possible. Thus, under this phase 3 study, the hydrogen production potential of the EAS region is estimated. The hydrogen production potential from unused energies will be less than 10% of the hydrogen demand potential estimated under phase 2 of this study, and it is mostly derived from low-ranked coal due to the limitation of existing data, especially on hydropower potential.

This study also seeks an optimal hydrogen supply chain between hydrogen-producing and -consuming countries in the EAS region through two hydrogen transport technologies by ship: methylcyclohexane (MCH) and liquid hydrogen. Generally, liquid hydrogen is appropriate for long-distance transport and large volumes. In addition, hydrogen shipment within ASEAN is important to optimise the hydrogen transport cost in the EAS region.

Under phase 3, two virtual hydrogen workshops were held for India and Malaysia to introduce major outcomes of the phase 2 study, including hydrogen production technologies and their costs, revision of EAS country hydrogen demand by 2040, and presentations on New Energy and Industrial Technology Development Organization (NEDO) hydrogen projects. For India and Malaysia, ERIA worked with the International Advanced Research Centre for Powder Metallurgy and New Materials to hold the workshop as well as the Ministry of Energy and Natural Resources, Government of Malaysia.

A low-carbon energy transition is the first priority, as announced at EAS Energy Ministers Meeting, hosted by Brunei Darussalam in September 2021. Use of hydrogen as a renewable energy was also highlighted to achieve a low-carbon energy transition. Consequently, the first EAS Hydrogen Working Group was created, consisting of Australia, Brunei Darussalam, China, India, Indonesia, Japan, Malaysia, New Zealand, and Thailand. It discussed the role of hydrogen in contributing to a low-carbon energy transition or carbon-neutral pathway for EAS countries. Australia, Japan, and New Zealand emphasised the importance of hydrogen in their carbon-neutral scenario or road map up to 2050. However, China, Brunei Darussalam, India, Indonesia, Malaysia, and Thailand still consider variable renewable energies, such as solar and wind, as ultimate energy sources to achieve their low-carbon energy transition.

ERIA then held the Second EAS Hydrogen Working Group meeting, which consisted of a brief presentation of the phase 3 study contents, including the review of hydrogen production technologies and their costs as well as an optimal hydrogen transport solution. There were also introductory presentations on hydrogen use for power generation instead of gas power generation and NEDO hydrogen projects. ERIA will continue to investigate wider uses of hydrogen in the EAS region through conferences, workshops, and meetings.

Chapter 1
Introduction

Hydrogen is a low- and/or zero-emissions energy technology. It is produced largely from fossil fuels using carbon capture, utilisation, and storage (CCUS) as well as from renewable energy electricity for water electrolysis. Hydrogen production from unutilised energy sources – that is, energy resources that physically exist but are not being used – is also possible. Unutilised energy sources include:

(i) **Low-ranked coal.** Low-ranked coal, such as lignite and brown coal, is found mostly in Australia and Indonesia, but is not used for environmental reasons, as they emit a lot of carbon dioxide (CO_2). If hydrogen is produced from low-ranked coal through gasification technology using CCUS, blue hydrogen can be produced.

(ii) **Flared gas**. Flared gas at oil and gas fields is classified as waste gas, but hydrogen can be recovered by using CCUS. Many countries in the East Asia Summit (EAS)[1] region – such as Australia, Brunei Darussalam, and Indonesia – produce a lot of flared gas.

(iii) **Hydropower in isolated areas.** Hydropower has significant potential in Sarawak, Malaysia and the North Kalimantan and Papua provinces of Indonesia. It has not been well developed in these areas due to the low electricity demand near these sites and the significant costs to construct transmission lines to urban areas. At these sites, hydrogen can be produced using water electrolysis technology and be transported by tankers.

(iv) **Solar photovoltaic (PV) systems.** To balance electricity supply and demand, surplus electricity generated by solar PV systems can be utilised. With this electricity, hydrogen can be produced through water electrolysis.

This phase 3 study – of the demand and supply potential of hydrogen energy in the EAS region – was conducted based on an analysis of the unused energy resources mentioned above for 2040. Due to technical difficulties, solar PV systems were deleted from the scope.

In the EAS region, some countries have the advantage of hydrogen production. Therefore, hydrogen networks – which connect both hydrogen-advantaged countries and -disadvantaged countries – must be developed. Using tankers, there are three ways to transport hydrogen from hydrogen-producing countries to -consuming countries: (i) ammonia (ii) methylcyclohexane (MCH), and (iii) liquid hydrogen.[2] Transport costs depend

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1 The EAS region includes Association of Southeast Asian Nations (ASEAN) Members (i.e. Brunei Darussalam, Cambodia, Indonesia, the Lao People's Democratic Republic [Lao PDR], Malaysia, Myanmar, the Philippines, Singapore, Thailand, and Viet Nam) plus Australia, China, India, Japan, the Republic of Korea, New Zealand, Russia, and the United States (US).

2 Ammonia consists of hydrogen and nitrogen, MCH consists of hydrogen and toluene, and hydrogen liquefied under –253°C. All have steps before and after transport to make the hydrogen transportable and then to return it to its original state (e.g. mixing hydrogen with nitrogen and toluene, separating hydrogen from ammonia and MCH, and liquification).

on distance and volume. This study also investigated the optimal hydrogen transport method, applying a linear programming approach to MCH and liquid hydrogen. This study omitted ammonia, because ammonia is already tradable.

Under this study, working group meetings, held virtually in 2021, discussed how hydrogen can contribute to carbon-neutral targets. Australia, Japan, and New Zealand emphasised the importance of hydrogen in achieving carbon-neutral status by 2050, but others remain focussed on renewable energy. During these meetings, the Economic Research Institute for the Association of Southeast Asian Nations (ASEAN) and East Asia (ERIA) shared outcomes from this phase 3 study as well as Japan's experience with hydrogen power generation and New Energy and Industrial Technology Development Organization (NEDO) hydrogen projects in Australia and Brunei Darussalam.

Further, two workshops were held in India and Malaysia, which introduced results from the phase 2 study, including a review of hydrogen production and cost, revision of hydrogen demand based on realistic assumptions, and an overview of hydrogen transport and costs for MCH and liquid hydrogen. India is currently conducting several hydrogen studies, so there were many fruitful discussions with Indian hydrogen experts. Yet hydrogen is still not a top energy policy in either country, and the Government of Malaysia intends to increase variable renewable energy, such as solar and wind, on its low-carbon energy transition pathway.

Chapter 2

Hydrogen Supply Potential

This section estimates the hydrogen supply potential in the EAS region.

1. Hydrogen Production Technologies

Hydrogen hardly exists as a molecule in nature – instead, it is found in the form of oxides or carbides (e.g. H_2O and CnHm). To obtain hydrogen, energy must be used for a chemical reaction that breaks, for instance, the H–O bond or C–H bond. Heat and electricity are generally used as the energy, but other methods use light or radiation. Industrial hydrogen production processes include steam reforming of light hydrocarbons, partial oxidation, gasification of coal, and water electrolysis.

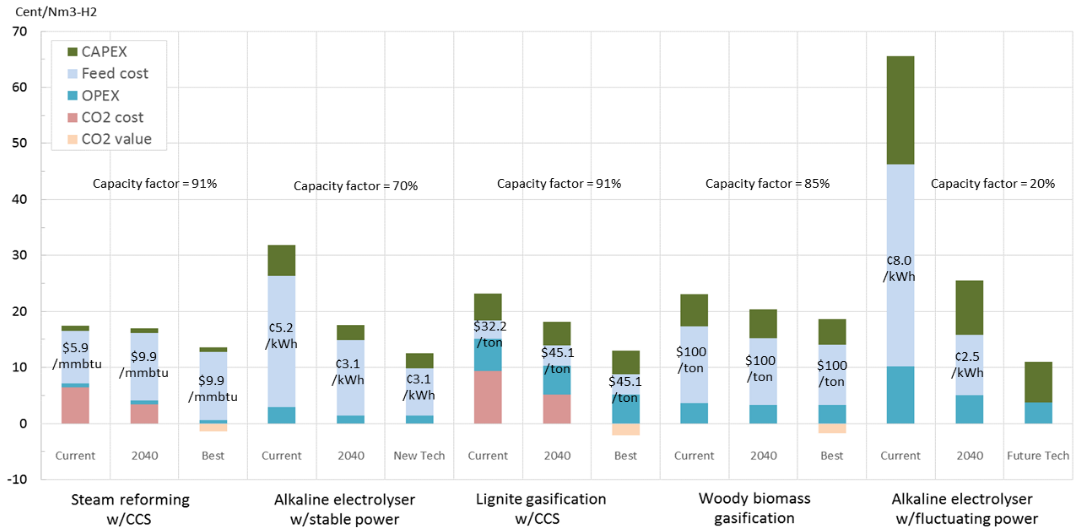
Table 2.1. Hydrogen Production Technologies

		Input Energy		
		Heat	**Electricity**	**Other**
Feedstock	**Hydrocarbon**	Steam reforming Partial oxidation Autothermal reforming Thermal cracking		
	Water	Thermochemical water splitting	Alkaline electrolysis Polymer electrolyte membrane (PEM) High-temperature steam reforming	Photolytic Biological Radiation

Source: DOE, Hydrogen Production Processes, https://www.energy.gov/eere/fuelcells/hydrogen-production-processes (accessed 18 September 2021).

Steam reforming of natural gas is the cheapest, while alkaline water electrolysis using variable renewable energy is the most expensive method (ERIA, 2019). The latter is expensive because the supply of electric power for water electrolysis is not stable, so the capacity factor of a water electrolysis device is low. Such hydrogen production costs can be halved, however, if a high operating rate can be maintained under stable power. Technological improvements may reduce the cost of alkaline water electrolysis, making it the most economical hydrogen production method.

Figure 2.1. Cost of Large-Scale Hydrogen Production



**1 : Feed Cost of Lignite gasification is based on FOT price in Intra-regional Group Countries.*
**2 : CCS cost is based on $70/t-CO2 for current and $48/t-CO2 for 2040 (CCS/Utilization Singapore Perspectives).*

CAPEX = capital expenses, CCS = carbon capture and storage, CO_2 = carbon dioxide, kWh = kilowatt-hour, mmbtu = metric million British thermal unit, OPEX = operating expenses.
Source: ERIA (2019a).

2. Hydrogen Production from Unused Energy

This phase 3 study focussed on unused energy for potential hydrogen production in 2040, specifically low-rank coal, flared gas, and untapped hydropower. Geographical coverage includes Australia, China, India, Japan, the Republic of Korea, New Zealand, as well as all of the ASEAN Members. Indonesia was divided into Kalimantan, Sumatra, Java, Sulawesi, Papua, and other regions. Only East Malaysia was targeted in Malaysia, because unused energy is concentrated in Saba and Sarawak states.

2.1. Low-Rank Coal

Coal is produced by carbonising plants over a long period of time. Low-rank coal, such as lignite or brown coal, is young coal that is not maturely carbonised. Low-rank coal has a high moisture and ash content, as well as a high oxygen content, so its calorific value is low. It is not suitable for long-distance transport or storage, because it is easily pulverised and can self-ignite. A special boiler is required for combustion, so it is not widely used. However, low-rank coal is plentiful and cheap. Therefore, if low-rank coal can be converted to hydrogen and used cleanly, it will be an effective use of resources.

Table 2.2 consolidates the amount of low-rank coal reserves in 2018. In the EAS region, about 70% of low-rank coal reserves are in Australia, followed by Indonesia, China, New Zealand, and India. These five countries constitute 97% of low-rank coal reserves in the EAS region.

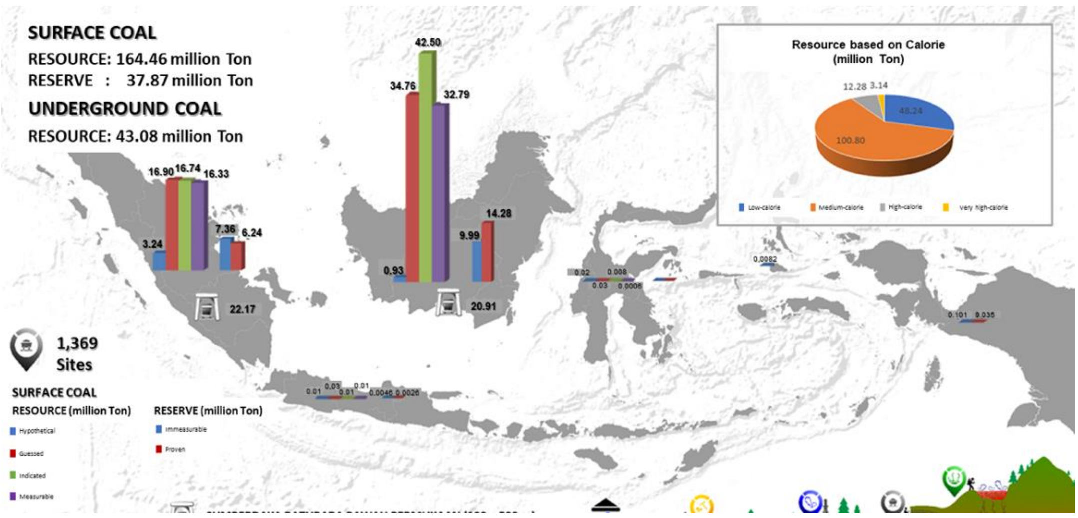
Table 2.2. Low-Rank Coal Reserves in the East Asia Summit Region
(million tons)

Country	Reserves	Resources	Remaining Potential
Australia	76,508	403,382	479,890
China	8,128	324,068	332,196
India	5,073	38,971	44,044
Indonesia	11,728	27,998	39,726
Japan	10	1,026	1,036
Lao PDR	499	22	521
Malaysia	78	817	896
Myanmar	3	2	5
New Zealand	6,750	4,600	11,350
Philippines	146	842	988
Thailand	1,063	826	1,889
Viet Nam	244	199,876	200,120

Lao PDR = Lao People's Democratic Republic.
Note: Reserves are defined as the 'proven volume of energy resources economically exploitable at today's prices and using today's technology'. In the meantime, resources are the 'proven amount of energy resources [that] cannot be exploited for technical and/or economic reasons, as well as unproven but geologically possible energy resources which may be exploitable in future'.
Source: BGR (2019).

In Indonesia, most coal resources are located in Kalimantan and on Sumatra. Coal reserves total about 32.79 billion tons in Kalimantan and 16.33 billion tons on Sumatra; the ratio of coal reserves between Kalimantan and Sumatra is about 2:1. This study used this ratio to split low-rank coal reserves and production in Indonesia.

Figure 2.2. Distribution of Coal Reserves in Indonesia, October 2018
(billion tons)



Source: MEMR (2018).

The produced amount of low-rank coal is not necessarily relevant to the amount of reserves in a country. China is the third-largest endowed country in the EAS region, accounting for 7% of the total, but the production volume is the largest in the region, accounting for 45% of the total. Indonesia has the second-largest production value, followed by India and Australia at about the same volume. Although New Zealand has the same amount of resources as China and India, its production volume remains at a level that does not appear in the statistics. Indeed, New Zealand does not have a policy to increase low-rank coal production in the future.

Table 2.3. Low-Rank Coal Reserves
(million tons)

	2014	**2015**	**2016**	**2017**	**2018**
Australia	58.0	61.0	59.8	56.1	45.1
China	145.0	140.0	140.0	145.0	150.0
India	48.3	43.8	45.2	46.7	45.3
Indonesia	60.0	60.0	60.0	60.0	60.0
Lao PDR	< 0.05	4.5	13.1	13.4	15.9
Thailand	18.0	15.2	17.0	16.3	14.9

Lao PDR = Lao People's Democratic Republic.
Source: BGR (2019).

From previous data, the amount of reserves and production of low-rank coal are expected to remain the same until 2050 in the EAS region. The target period of this study is up to 2040, but the remaining amount of low-rank coal is estimated until 2050, because the investment required for hydrogen production cannot be made unless sufficient reserves remain for a certain period beyond 2040, as well as to make a safe-side estimation:

Remaining reserves in 2050 (2040) = Reserve in 2018 – (production in 2018 x 32 years) (1)

From this equation, it can be assumed that low-rank coal reserves in the Lao People's Democratic Republic (Lao PDR), for example, will be depleted before 2050. There is also an insufficient amount of low-rank coal reserves in Japan and Myanmar.[3]

[3] For instance, to operate 100 megawatts (MW) of a pure hydrogen-fired combined-cycle gas turbine power plant, 4.2 petajoules (PJ) of hydrogen is needed per year (i.e. 60% of thermal efficiency, 80% of capacity factor). To fuel 5,000 heavy-duty trucks, 2.5 PJ of hydrogen is needed per year (i.e. 4 kilometres [km] per litre of diesel-equivalent fuel economy and 100,000 km of driving distance). However, 10 million tons of low-rank coal for Japan can only produce 37 PJ of hydrogen, while 3 million tons for Myanmar can only produce 13 PJ. Thus, the operating life of such hydrogen production projects are less than 10 years, which may be too short to anticipate sufficient profits that can support an investment decision.

Table 2.4. Available Amount of Low-Rank Coal Reserves for Producing Hydrogen

	Reserves, 2018	Lignite Production, 2018	Lignite Consumption, 2019–2050	Remaining Reserves, 2050	Reserves Reduction, 2018–2050	Ratio, 2050
	million tons	million tons	million tons	million tons	%	
Australia	76,508	45	1,443	75,065	–2	1,664
Brunei Darussalam						
Cambodia						
China	8,128	150	4,800	3,328	–59	22
India	5,073	45	1,450	3,623	–29	80
Indonesia	11,728	60	1,920	9,808	–16	163
Kalimantan	7,819	16	509	7,310	–7	460
Sumatera	3,909	15	467	3,442	–12	236
Java					0	
Sulawesi					0	
Papua					0	
Others					0	
Japan	10			10	0	
Korea, Republic of						
Lao PDR	499	16	509		–100	
Malaysia	78			78	0	
Myanmar	3			3	0	
New Zealand	6,750			6,750	0	
Philippines	146			146		
Singapore					0	
Thailand	1,062	15	467	596	–44	41
Viet Nam	244			244	0	

Lao PDR = Lao People's Democratic Republic.
Source: Authors' calculations.

This study then estimated the amount of hydrogen production under the following conditions. For the commercialisation rate of remaining reserves, the study assumed 75% for the high case and 25% for the low case. Regarding yield of hydrogen from the coal gasification process, the study referred to JST (2019), which estimated the amount of hydrogen produced applying coal gasification technology to two types of coal (i.e. lignite and bituminous). For lignite coal, JST (2019) found that the yield of hydrogen production is 21 tons of lignite per ton of hydrogen. If the net calorific value (NCV) of lignite is applied to JST (2019),[4] the hydrogen production efficiency from lignite is 50%. Finally, the NCV of low-rank coal was provided by IEA (2020a), which supplied the average NCV of lignite in each country. If data were not available, the study applied 10,000 kilojoules per kilogram of NCV for unit conversion. The potential of hydrogen production from low-rank coal is presented in Table 2.5.

[4] The NCV of lignite is 11.5 megajoules per kilogram, and of hydrogen is 120 megajoules per kilogram.

Table 2.5. Hydrogen Production Potential from Low-Rank Coal

	Remaining Reserves, 2040	NCV of Lignite	Potential, High Case		Potential, Low Case	
	million tons	kJ/kg	PJ	million Nm^3	PJ	million Nm^3
Australia	75,065	9,800	274,150	21,499	91,383	7,166
Brunei Darussalam						
Cambodia						
China	3,328	10,000	12,402	973	4,143	324
India	3,623	9,546	12,890	1,011	4,297	337
Indonesia	9,808	5,100	18,641	1,462	6,214	487
Kalimantan	7,310	5,100	13,893	1,090	4,631	363
Sumatera	3,442	5,100	6,542	513	2,181	171
Java		5,100				
Sulawesi		5,100				
Papua		5,100				
Others		5,100				
Japan	10	10,000				
Korea, Republic of						
Lao PDR		9,630				
Malaysia	78	10,000	291	23	97	8
Myanmar	3	11,900				
New Zealand	6,750	17,082	42,970	3,370	14,323	1,123
Philippines	146	10,000	544	43	181	14
Singapore						
Thailand	596	10,571	2,347	184	782	61
Viet Nam	244	10,000	909	71	303	24

Lao PDR = Lao People's Democratic Republic, NCV = net caloric value, Nm^3 = normal cubic metre.
Source: Authors' calculations.

Australia has the greatest hydrogen production potential from low-rank coal, accounting for 71% of the EAS region's potential. This is because the amount of available reserves is large compared to other countries. The next greatest potential is possessed by New Zealand, which has 11% of the total region's potential due to its high NCV. However, although Indonesia has the largest amount of available reserves amongst countries ranked second or lower, the amount of hydrogen that can be produced is relatively small due to Indonesia's low NCV.

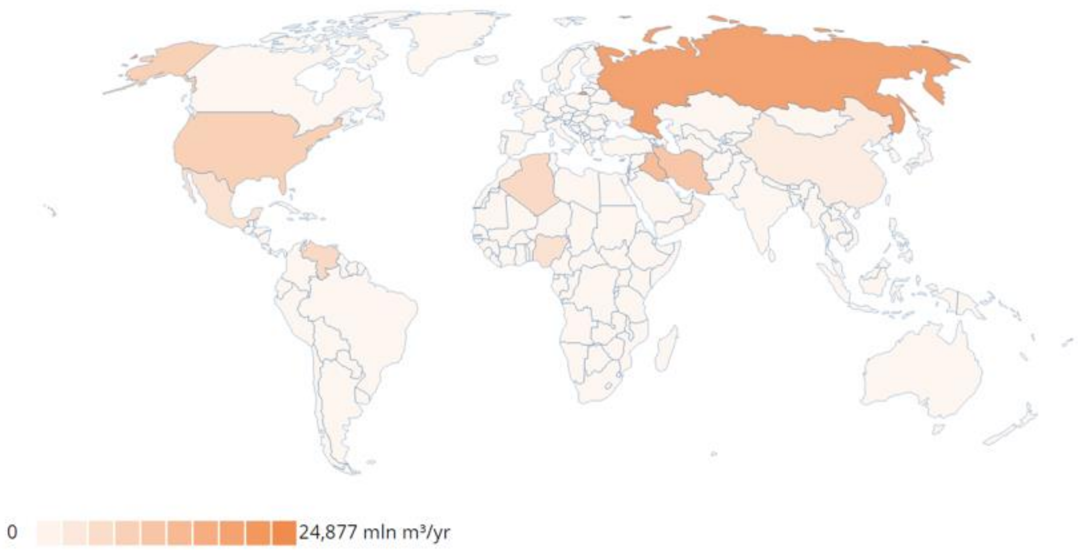
2.2. Flared Natural Gas

Flared gas is gaseous hydrocarbon that is burned for disposal; there are two types. The first is an associated gas created as a by-product of crude oil production, so the amount of flare is linked to the amount of crude oil produced. Since the associated gas contains volatile components, there is a danger of explosion, so it is incinerated on the stack as a safety measure. In addition, since oil is generally traded at a higher price than natural gas and additional costs are required for the recovery and processing of an associated gas, it is incinerated from the viewpoint of business feasibility. Flared gas, in this case, is routine as long as there is crude oil production.

The other type is light by-product gases generated from manufacturing processes such as petroleum refining, chemical industrial processes, and steel making. Since the by-product gas also has dangers, including volatility, toxicity, and odour, it is incinerated and then released into the atmosphere. In many cases, this flared gas is reused as energy, thus not routinely but temporarily generated. By considering this different nature of flared gas (i.e. routine or not), this study targeted routine generation, or that generated as a by-product of crude oil production.

In addition to the CO_2 emissions from the combustion of flared gas, methane – which has an 80 times greater greenhouse effect than CO_2 – is also released into the atmosphere when combustion is incomplete. In addition to damaging the environment, incinerating mined natural gas is a loss in terms of resource efficiency. The World Bank is thus working to eliminate routine gas flaring through its Global Gas Flaring Reduction Partnership. It has set a goal of zero routine flaring by 2030.[5] Using otherwise flared gas as a feedstock for hydrogen production is consistent with the World Bank's initiative.

Figure 2.3. Routine Gas Flares Worldwide, 2020



m^3 = cubic metre.
Source: World Bank, Individual Flare Sites, https://www.ggfrdata.org/ (accessed September 2021).

[5] World Bank, Global Gas Flaring Reduction Partnership, https://www.worldbank.org/en/programs/gasflaringreduction#7 (accessed 18 September 2021)

According to World Bank, about 10.0 billion cubic metres (bcm) of natural gas is flared annually in the EAS region. This amount is equivalent to Viet Nam's natural gas consumption in 2019 (BP, 2020). If such flared gas can be transformed into hydrogen and used cleanly, this can reduce greenhouse gases and strengthen energy supply stability.

Table 2.6. Amount of Flared Gas, East Asian Summit Region
(bcm)

	2015	2016	2017	2018	2019
Australia	1.14	0.73	0.66	0.86	1.39
Brunei Darussalam	0.21	0.28	0.30	0.21	0.31
China	2.08	1.96	1.56	1.82	2.03
India	2.20	2.06	1.50	1.34	1.31
Indonesia	2.91	2.77	2.33	2.06	2.00
Malaysia	3.72	3.16	2.83	2.25	2.37
Myanmar	0.06	0.04	0.04	0.03	0.02
New Zealand	0.13	0.10	0.10	0.06	0.05
Philippines	0.16	0.17	0.13	0.12	0.08
Thailand	0.43	0.40	0.37	0.33	0.32
Viet Nam	1.03	0.92	0.98	0.74	0.78

Source: World Bank, Global Gas Flaring Reduction Partnership, https://www.worldbank.org/en/programs/gasflaringreduction#7 (accessed 18 September 2021)

In Indonesia, the largest oil-producing area is central Sumatra, which includes the Duri and Minas oil fields. Oil production in these two areas accounted for more than half of national production. Other major oil-producing areas are Java and Kalimantan.[6] Therefore, this study assumed 50% of oil production (i.e. gas flaring) comes from Sumatra, and 25% each from Java and Kalimantan.

As mentioned previously, the amount of flared gas changes in conjunction with the amount of crude oil produced. Thus, if crude oil production ceases in a country, the amount of flared gas will also disappear. Therefore, the study reviewed the exploitable years of oil in oil-producing countries in the EAS region (i.e. the reserve–production ratio). The situation varies from country to country, but in general, the amount of oil resources in oil-producing countries is low compared to their oil production. In many countries, the reserve–production ratio is 15–30 years, except for Viet Nam's 51 years. In addition, New Zealand and Thailand have ratios of only 4.6 and 1.7 years, respectively; it is highly likely that their oil reserves will be depleted in the near future. Indonesia also has a low ratio of 8.7 years, but the ongoing resource exploration may succeed in uncovering new reserves. Further, there is an

6 Indonesia Petroleum Association, Oil, https://www.ipa.or.id/en/the-industry/oil (accessed 18 September 2021).

insufficient amount of flared gas in Brunei Darussalam, Myanmar, and the Philippines.[7] This study thus assumed that crude oil production – as well as flared gas – will dissipate as of 2040 in countries with an reserve–production ratio of less than 5 years. For other countries, the amount of flared gas in 2040 was assumed to be the same as it is today.

Table 2.7. Amount of Flared Gas and Ratio of Oil in the East Asia Summit Region

	Flared Gas, 2019 (bcm)	**R/P Ratio of Oil Reserves, 2019**	**Flared Gas, 2040** (bcm)
Australia	1.390	13.4	1.390
Brunei Darussalam	0.307	24.8	0.307
Cambodia			
China	2.025	18.7	2.025
India	1.310	15.5	1.310
Indonesia	2.004	8.7	2.004
Kalimantan	0.501		0.501
Sumatera	1.002		1.002
Java	0.501		0.501
Sulawesi	0		0
Papua	0		0
Others	0		0
Japan			
Korea, Republic of			
Lao PDR			
Malaysia	2.368	11.9	2.368
Myanmar	0.023	34.6	0.023
New Zealand	0.048	4.6	0
Philippines	0.084	29.0	0.084
Singapore			
Thailand	0.315	1.7	0
Viet Nam	0.781	51.0	0.781

bcm = billion cubic metres, Lao PDR = Lao People's Democratic Republic, R/P = reserve–production.
Sources: BP (2020); World Bank, Global Gas Flaring Reduction Partnership, https://www.worldbank.org/en/programs/gasflaringreduction#7 (accessed 18 September 2021); CIA, 'Burma', The World Factbook, https://www.cia.gov/the-world-factbook/countries/burma/#energy (accessed 18 September 2021); MBIE (2020); GOP (2021).

This study estimated the amount of hydrogen production under the following conditions. It referred to Iseki (2012), which showed the efficiency of hydrogen production from the steam-reforming method and pressure swing absorption technology to purify hydrogen. It noted

[7] As noted in the previous section for low-rank coal, for instance, to operate 100 MW of a pure hydrogen-fired combined-cycle gas turbine power plant, 4.2 PJ of hydrogen is needed per year. For instance, to fuel 5,000 heavy-duty trucks, 2.5 PJ of hydrogen is needed per year. Yet estimates show that Brunei Darussalam, Myanmar, and the Philippines can only produce 6 PJ, 1 PJ, and 4 PJ, respectively, of hydrogen from their flared gas.

that the efficiency is 60%–70% – 70% efficiency with technological improvement. Moreover, the gross calorific value (GCV) of natural gas was provided by IEA (2020a).

The potential of hydrogen production from flared gas in the region is presented in Table 2.8. Malaysia has the highest potential at 65 PJ, followed by Indonesia and China. Australia, India, and Viet Nam also have some potential.

Table 2.8. Hydrogen Production Potential from Flared Gas, East Asia Summit Region

	Flared Gas, 2040	**GCV of Natural Gas**	**Hydrogen Production Potential**	
	(bcm)	(kJ/m^3)	(PJ)	(million Nm^3)
Australia	1.390	39,914	39	3.0
Brunei Darussalam	0.307	42,000		
Cambodia				
China	2.025	38,931	55	4.3
India	1.31	39,000	36	2.8
Indonesia	2.004	40,600	57	4.5
Kalimantan	0.501	40,600	14	1.1
Sumatera	1.002	40,600	28	2.2
Java	0.501	40,600	14	1.1
Sulawesi	0	40,600		
Papua	0	40,600		
Others	0	40,600		
Japan				
Korea, Republic of				
Lao PDR				
Malaysia	2.368	39,249	65	5.1
Myanmar	0.023	39,269		
New Zealand	0	39,077		
Philippines	0.084	38,549		
Singapore				
Thailand	0.315	36,396		
Viet Nam	0.781	38,612	21	1.7

bcm = billion cubic metres, GCV = gross caloric value, kJ = kilojoule, Lao PDR = Lao People's Democratic Republic, m^3 = cubic metre, Nm^3 = normal cubic metre, PJ = petajoule.
Source: Authors' calculations.

2.3. Potential of Carbon Capture, Utilisation, and Storage

CCUS is indispensable for hydrogen production from low-rank coal or flared gas, making it free from CO_2 emissions. For this study, the carbon content value of low-rank coal was represented by lignite, and flared gas by natural gas. By applying these values from IEA (2020b), CO_2 emissions from feedstock consumption were estimated.[8]

For Australia and India, the discovered storage capacity – the sum of the capacity and sub-commercial capacity – is smaller than required. Therefore, both countries need to explore additional storage sites as well as to develop their discovered capacity. Alternatively, carbon can be recycled to conserve their limited CCUS capacities. In China, the sub-commercial capacity is sufficient to absorb possible CO_2 emissions from producing blue hydrogen.

Table 2.9. Carbon Dioxide Emissions from Feedstock Consumption and Carbon Capture and Storage Potential

	Unit	Australia	China	India
Carbon Content of Lignite	kg/GJ	27.6	27.6	27.6
Low-Rank Coal Consumption, High Case	million tons	56,299	2,496	2,718
Net Calorific Value	kJ/kg	9,800	10,000	9,546
CO_2 Emissions from Low-Rank Coal	Gton	56.0	2.5	2.6
Carbon Content of Natural Gas	kg-C/GJ	15.3	15.3	15.3
Flared Gas Consumption	bcm	1.39	2.03	1.31
Gross Calorific Value of Natural Gas	kJ/m^3	39,914	38,931	39,000
CO_2 Emissions from Flared Gas	Gton	0.0031	0.0044	0.0029
Potential of Carbon Capture, Utilisation, and Storage	Gton			
Capacity		0.12	0	0
Sub-Commercial		17	105	1
Undiscovered		414	3,067	63

bcm = billion cubic metres, CO_2 = carbon dioxide, GJ = gigajoule, Gton = gigaton, kg = kilogram, m^3 = cubic metre.
Notes: Apply the high case for low-rank coal consumption. Capacity signifies economically viable resources; sub-commercial denotes discovered but uncertain economic viability and possible inaccessibility; and undiscovered are geographically unconfirmed resources.
Source: IEA (2020a), IEA (2020b), Pale Blue Dot Energy (2020).

2.4. Untapped Hydropower Resources

The EAS region, which has a rainy climate, has great potential for hydropower generation. Hydrogen can be produced from hydropower, which is a clean energy with no carbon emissions.

[8] In a plant, energy input for the transformation process is added to increase CO_2 emissions, which is neglected in this analysis.

Table 2.10. Hydropower Resources in the East Asia Summit Region
(gigawatt)

Country	Hydropower Resources
Australia	
Brunei Darussalam	
Cambodia	10
China	600
India	145
Indonesia	75
Japan	
Korea, Republic of	
Lao PDR	26
Malaysia	29
Myanmar	100
New Zealand	
Philippines	13
Singapore	
Thailand	15
Viet Nam	25–26

Lao PDR = Lao People's Democratic Republic.
Sources: Aroonrat and Wongwises (2015); Erdiwansyah et al. (2020); ERIA (2019b); EVN, Overview of Hydropower in Viet Nam', https://en.evn.com.vn/d6/news/Overview-of-hydropower-in-Vietnam-66-163-1514.aspx (accessed September 2021); IHA, 'China', Country Profiles, https://www.hydropower.org/country-profiles/china (accessed September 2021); IHA, 'Myanmar', Country Profiles, https://www.hydropower.org/country-profiles/myanmar (accessed September 2021); IRENA (2017); and Verma (2020).

In Indonesia, Papua and Kalimantan provinces have the greatest resources, but they are the least hydropower-developed regions – meaning they have the largest remaining resources as well. Sumatra and Sulawesi provinces also have large resources, and small resources can be found in Java. This study applied the ratios in Table 2.11 to split hydropower resources in Indonesia.

Table 2.11. Hydropower Resources in Indonesia by Region
(megawatts)

			Remaining Resources	
Province	**Resources**	**Developed**	**Capacity**	**Share to Total**
Kalimantan	21,581	32	21,549	31%
Sumatra	15,579	1,680	13,900	20%
Java	4,199	2,598	1,601	2%
Sulawesi	10,307	844	9,463	14%
Maluku	430		430	1%
Bali – Nusa Tenggara	624	6	618	1%
Papua	22,371	6	22,365	32%
Total	**75,091**	**5,166**	**69,925**	

Source: Utomo (2017).

Hydropower can harnessed in two ways. It can be directly used as electricity, or as an input energy for electrolysis to produce hydrogen. Therefore, hydropower's capacity for electricity generation is set off from the remaining resources.

The study first defined how many hydropower resources are used to generate electricity. IEA (2020c) outlined the prospect of hydropower development for electricity generation in two different scenarios: the stated policy scenario (STEPS) and sustainable development scenario (SDS). China will consume 156–211 gigawatts (GW) of hydropower resources for generating electricity from 2018 to 2040, equivalent to 26%–35% of total resources observed today. Similarly, in India, 51–68 GW of resources will be consumed for generating electricity, 35%–47% of total resources today. In ASEAN, 57–121 GW of resources will be exploited, 20%–41% of total resources today (Table 2.12).

Table 2.12. Hydropower Development Prospects for Electricity Generation, Selected Areas

Country	Scenario	Prospect	Unit	2018	2025	2030	2040	2018–2040
China	STEPS	Output	TWh	1,199	1,297	1,398	1,568	369
		Capacity	GW	352	411	446	508	156
		Capacity Factor		39%	36%	36%	35%	
	SDS	Output	TWh	1,199	1,345	1,507	1,701	502
		Capacity	GW	352	433	495	563	211
		Capacity Factor		39%	35%	35%	34%	
India	STEPS	Output	TWh	151	177	226	307	156
		Capacity	GW	49	60	76	101	51
		Capacity Factor		35%	33%	34%	35%	
	SDS	Output	TWh	151	196	258	361	210
		Capacity	GW	49	67	86	117	68
		Capacity Factor		35%	33%	34%	35%	
ASEAN	STEPS	Output	TWh	190	180	245	337	147
		Capacity	GW	46	56	77	104	57
		Capacity Factor		47%	37%	36%	37%	
	SDS	Output	TWh	190	223	327	537	
		Capacity	GW	46	72	103	167	
		Capacity Factor		47%	36%	36%	37%	

ASEAN = Association of Southeast Asian Nations, GW = gigawatt, SDS = sustainable development scenario, STEPS = stated policy scenario, TWh = terawatt-hour.
Source: IEA (2020c).

The remaining hydropower resources for producing hydrogen can be derived by extracting cumulative hydropower development for generating electricity from total resources. For ASEAN Members, the study applied the single common coefficient of 20% for STEPS and 40% for SDS to calculate the cumulative hydropower development for generating electricity.

Table 2.13. Remaining Hydropower Resources for Producing Hydrogen, East Asia Summit Region
(GW)

	Current Hydropower Resources	Hydropower for Electricity, STEPS	Maximum Remaining Hydropower Resources, 2040	Hydropower for Electricity, 2018–2040, SDS	Minimum Remaining Hydropower Resources, 2040
Australia					
Brunei Darussalam					
Cambodia	10	2	8	4	6
China	600	156	444	211	389
India	145	51	94	68	77
Indonesia	70	14	56	28	42
Kalimantan	21	4	17	8	13
Sumatera	14	3	11	6	8
Java	4	1	3	1	2
Sulawesi	11	2	8	4	6
Papua	21	4	17	8	13
Others					
Japan					
Korea, Republic of					
Lao PDR	26	5	21	10	16
Malaysia	29	6	23	12	17
Myanmar	100	20	80	40	60
New Zealand					
Philippines	13	3	10	5	8
Singapore					
Thailand	15	3	12	6	9
Viet Nam	25	5	20	10	15

Lao PDR = Lao People's Democratic Republic, SDS = sustainable development scenario, STEPS = stated policy scenario.
Source: Authors' calculations.

The study estimated the amount of hydrogen production under the following conditions. Regarding the commercialisation rate of the remaining potential, the study assumed 75% for the high case and 25% for the low case. It also estimated the capacity factor of hydropower in China, India, and ASEAN from IEA (2020c), and assumed the same for 2040. For ASEAN Members, a common capacity factor of 47% was applied to every country. It also applied, from catalogue data of existing electrolysers in the world, 5 kilowatt-hours per normal cubic metre (Nm^3) of hydrogen yield.

The estimated potential of hydrogen production from untapped hydropower resources is presented in Table 2.14. China possesses the greatest potential to produce hydrogen from hydropower, thanks to its large endowment of resources. Other significant potential can be seen in India, Indonesia, and Myanmar.

Table 2.14. Hydrogen-Producing Potential from Untapped Resources, East Asia Summit Region

	Maximum Remaining Hydropower Resources, 2040	Minimum Remaining Hydropower Resources, 2040	Capacity Factor, 2018	Potential/ Maximum Potential and High Case		Potential/ Minimum Potential and Low Case	
	(GW)	(GW)	(%)	(PJ)	(Nm^3 million)	(PJ)	(Nm^3 million)
Australia							
Brunei Darussalam							
Cambodia	8	6	47	63	5	16	1
China	444	389	39	2,901	227	848	67
India	94	77	35	549	43	150	12
Indonesia	56	42	47	441	35	110	9
Kalimantan	17	13	47	132	10	33	3
Sumatera	11	8	47	88	7	22	2
Java	3	2	47	22	2	6	0
Sulawesi	8	6	47	66	5	17	1
Papua	17	13	47	132	10	33	3
Others							
Japan							
Korea, Republic of							
Lao PDR	21	16	47	164	13	41	3
Malaysia	23	17	47	183	14	46	4
Myanmar	80	60	47	630	49	158	12
New Zealand							
Philippines	10	8	47	82	6	20	2
Singapore							
Thailand	12	49	47	95	7	24	2
Viet Nam	20	15	47	158	12	39	3

GW = gigawatt, Lao PDR = Lao People's Democratic Republic, PJ = petajoule, Nm^3 = normal cubic metre.
Source: Authors' calculations.

3. Summary and Discussion

3.1. Potential Hydrogen Production from Unused Energies

From the study, low-rank coal emerged as having the greatest hydrogen production potential. This is true for most countries in the EAS region, except Brunei Darussalam, Cambodia, the Lao PDR, and Myanmar. Cambodia, the Lao PDR, and Myanmar have greater potential in utilising untapped hydropower.

Table 2.15. Hydrogen-Producing Potential from Unused Energies, East Asia Summit Region
(million normal cubic metres)

	Low-Rank Coal		Flared Gas	Untapped Hydropower		Total Production Potential	
	Max	Min		Max	Min	Max	Min
Australia	21,499	7,166	3			21,502	7,169
Brunei Darussalam			1			1	1
Cambodia				5	1	5	1
China	973	324	4	227	67	1,204	395
India	1,011	337	3	43	12	1,057	352
Indonesia	1,462	487	4	35	9	1,501	500
Kalimantan	1,090	363	1	10	3	1,101	367
Sumatera	513	171	2	7	2	522	175
Java			1	2	0	3	2
Sulawesi				5	1	5	1
Papua				10	3	10	3
Others							
Japan							
Korea, Republic of							
Lao PDR				13	3	13	3
Malaysia	23	8	5	14	4	42	16
Myanmar			0	49	12	49	12
New Zealand	3,370	1,123				3,370	1,123
Philippines	43	14	0	6	2	49	16
Singapore							
Thailand	184	61		7	2	192	63
Viet Nam	71	24	2	12	3	85	29

Lao PDR = Lao People's Democratic Republic.
Source: Authors' calculations.

3.2. Supply and Demand Balance

This section compares the potential of hydrogen production with hydrogen demand estimated in ERIA (2020). The comparison indicates that the hydrogen production potential from unused energies is very small compared to the possible demand, with a few exceptions (Table 2.16). Australia, the Lao PDR, and New Zealand can become net exporters of hydrogen.

Table 2.16. Hydrogen-Producing Potential from Unused Energies
(million normal cubic metres)

	Production Potential		Demand Potential	Sufficiency Rate	
	Max	Min		Max	Min
Australia	21,502	7,169	13,974	154%	51%
Brunei Darussalam	1	1	1,775	0%	0%
Cambodia	5	1	352	1%	0%
China	1,204	395	163,408	1%	0%
India	1,057	352	11,990	9%	3%
Indonesia	1,501	500	44,807	3%	1%
Japan			29,252	0%	0%
Korea, Republic of			41,558	0%	0%
Lao PDR	13	3	9	137%	34%
Malaysia	42	16	24,034	0%	0%
Myanmar	49	12	1,263	4%	1%
New Zealand	3,370	1,123	1,065	317%	106%
Philippines	49	16	4,551	1%	0%
Singapore			15,098	0%	0%
Thailand	192	63	12,993	1%	0%
Viet Nam	85	29	3,668	2%	1%
	29,070	9,681	369,796	8%	3%

Lao PDR = Lao People's Democratic Republic.
Source: Authors' calculations, ERIA (2020).

3.3. Discussion

The phase 3 study had difficulty in obtaining consistent and comprehensive datasets for analysis, particularly resource data. A country may have greater – and others may have lesser – potential than this study indicated if different datasets are used. Therefore, it is appropriate to regard the results as indicative.

Further, a country must apply CCUS when producing hydrogen from fossil fuels. However, as previously discussed, estimated CO_2 storage capacity is not necessarily sufficient to decarbonise all hydrogen in the region. Evaluation of CCUS potential is immature in every country in this region. Therefore, countries should continue to explore CO_2 storage sites, develop carbon-recycling technologies, and encourage hydrogen-producing projects.

The study only examined the technical aspects of hydrogen production – not policy, regulatory frameworks, financing, or public acceptance.

Chapter 3

Optimal Hydrogen Supply Chain in East Asia

1. Background

As previously stated, hydrogen is produced from fossil fuels and water. Therefore, hydrogen production sites are different from hydrogen consumption sites. The development of a hydrogen supply network – the hydrogen supply chain – is thus key in the EAS region. Based on the hydrogen production of hydrogen-exporting countries, hydrogen consumption of hydrogen-importing countries, distances between hydrogen-exporting and -importing countries, and transport costs, this section outlines optimal hydrogen transport routes and amounts in 2040 when hydrogen will be used commercially as a zero-emission fuel.

2. Optimisation Approach

To find an optimal hydrogen supply chain solution in 2040, the linear programming approach was applied, and its model structure consists of following blocks.

Hydrogen consumption block. This is the hydrogen consumption amount (Nm^3) of hydrogen-importing countries in the EAS region:

$$\sum_i \sum_k X_{jjk} = HC_j \qquad (2)$$

Where:
X_{ijk} = the hydrogen transport amount from exporting country *i* to importing country *j* by transport mode *k,* and
HC_j = hydrogen consumption of importing country *j.*

Hydrogen production block. This is the hydrogen production amount (Nm^3) of hydrogen-exporting countries in the EAS region:

$$\sum_j \sum_k \boldsymbol{X_{ijk}} = \boldsymbol{HP_i} \qquad (3)$$

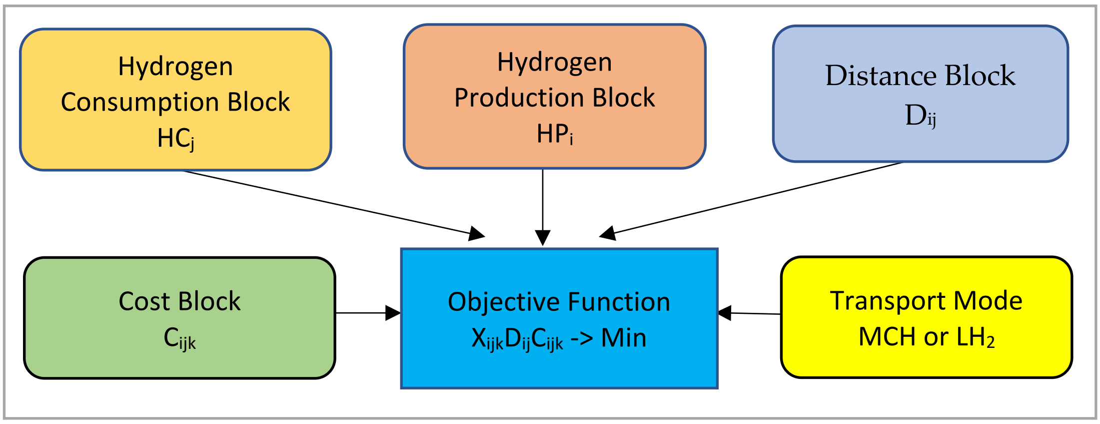
Where:
X_{ijk} = the hydrogen transport amount from exporting country *i* to importing country *j* by transport mode *k,* and
HP_i = hydrogen production amount of exporting country *i.*

Distance block. This is the distance (km) between hydrogen-exporting and -importing countries, where D_{ij} is the distance between hydrogen-exporting country *i* and hydrogen-importing country *j.*

Cost block. This is the hydrogen transport cost ($ per Nm^3 per km) from exporting country *i* to hydrogen-importing country *j* by transport mode *k*, where C_{ijk} is the transport cost from hydrogen-exporting country *i* and hydrogen-importing country *j* by transport mode *k.*
Objective function.

$$\sum_i \sum_j \sum_k X_{ijk} D_{ij} C_{ijk} \quad -> MIN \qquad (4)$$

Figure 3.1. Hydrogen Optimisation – Linear Programming Model



Source: Author.

3. Model Assumptions

3.1 Selection of Hydrogen-Exporting and -Importing Countries

As hydrogen-exporting countries in EAS region, the following five countries and areas were selected for developing the hydrogen linear programming model:

(i) **Australia.** Large potential of fossil fuels (i.e. coal and gas) and variable renewable energy (e.g. solar PV systems).

(ii) **Brunei Darussalam.** Some potential of fossil fuels, such as gas.

(iii) **Indonesia.** Large potential of fossil fuels (i.e. coal and gas) and hydropower.

(iv) **Sarawak, Malaysia.** Large hydropower potential.

(v) **New Zealand.** Large potential of hydropower, wind power, and geothermal power.

In addition, the ports of the five hydrogen-exporting countries and areas were defined:

(i) **Australia.** Port of Melbourne.

(ii) **Brunei Darussalam.** Port of Muara.

(iii) **Indonesia.** Port of Bontang.

(iv) **Sarawak, Malaysia:** Senari Port, Kuching.

(v) **New Zealand:** Lyttelton Port, Christchurch.

The shipped amount of hydrogen from each port in 2040 is outlined in Table 3.1.

Table 3.1. Supply Amount of Hydrogen
(million normal cubic metres)

Country	Amount
Australia	284,313
Brunei Darussalam	26,979
Indonesia	209,603
Malaysia	128,667
New Zealand	22,828

Source: ERIA (2018).

As hydrogen-importing countries in the EAS region, the following five countries were selected for developing the linear programming model:

(i) **Japan.** Replacing gas power generation by hydrogen power generation and internal combustion engine (ICE) by fuel cell vehicles (FCVs).

(ii) **Korea**. Replacing gas power generation by hydrogen power generation and ICE by FCVs.

(iii) **Peninsular Malaysia.** Replacing gas power generation by hydrogen power generation and ICE by FCVs.

(iv) **Singapore.** Replacing gas power generation by hydrogen power generation.

(v) **Thailand.** Replacing gas power generation by hydrogen power generation and ICE by FCVs.

The receiving ports of the five hydrogen exporting countries are outlined below:

(i) **Japan.** Port of Tokyo.

(ii) **Korea.** Port of Incheon.

(iii) **Malaysia.** Port of Kuantan.

(iv) **Singapore.** Port of Singapore

(v) **Thailand.** Khlong Toei Port, Bangkok.

The amount of hydrogen received in each port of the five hydrogen-exporting countries in 2040 is outlined in Table 3.2.

Table 3.2. Demand Amount for Hydrogen

(million normal cubic metres)

Country	Amount
Japan	302,811
Korea, Republic of	193,609
Malaysia	106,474
Singapore	14,707
Thailand	54,788

Source: ERIA (2019a).

3.2. Distance between Hydrogen Shipping Ports and Receiving Ports

Distances between hydrogen-exporting and -importing ports are defined in Table 3.3.

Table 3.3. Distances between Hydrogen Supply and Demand Places
(kilometres)

Origin/Destination	Port of Melbourne, Australia	Port of Muara, Brunei Darussalam	Senari Port, Kuching, Malaysia	Port of Bontang, Indonesia	Lyttelton Port, Christchurch, New Zealand
Port of Tokyo, Japan	9,910.0	4,342.9	6,172.7	5,817.1	11,626.9
Port of Incheon, Korea	11,191.6	3,802.2	5,144.9	5,104.1	12,862.1
Port of Singapore	8,067.3	1,335.3	1,000.1	2,468.7	11,708.3
Port of Kuantan, Malaysia	8,461.8	1,400.1	981.6	2,776.1	12,101.0
Port of Laem Chabang, Thailand	9,617.4	2,340.9	2,137.2	3,648.4	12,917.7
Khlong Toei Port, Bangkok, Thailand	9,741.5	2,465.0	2,261.3	3,772.5	13,041.8

Note: The two Thailand ports are in the Bangkok area, but both ports are very close in case of long-distance transport; thus, both ports are merged into Port Laem Chabang to represent the port of Bangkok.
Source: Ports.com, http://ports.com/sea-route/#/?a=0&b=0&c=Port%20of%20Melbourne&d=Port%20of%20Tokyo (accessed 25 February 2021).

3.3. Hydrogen Transport Costs

Two hydrogen transport methods were applied to the linear programming model: MCH and liquefied hydrogen. The unit cost of hydrogen transport was difficult to set due to varied transport conditions and uncertainties. Thus, under the following assumed conditions and forecasts, the unit cost curves are in Figures 3.2 and 3.3:

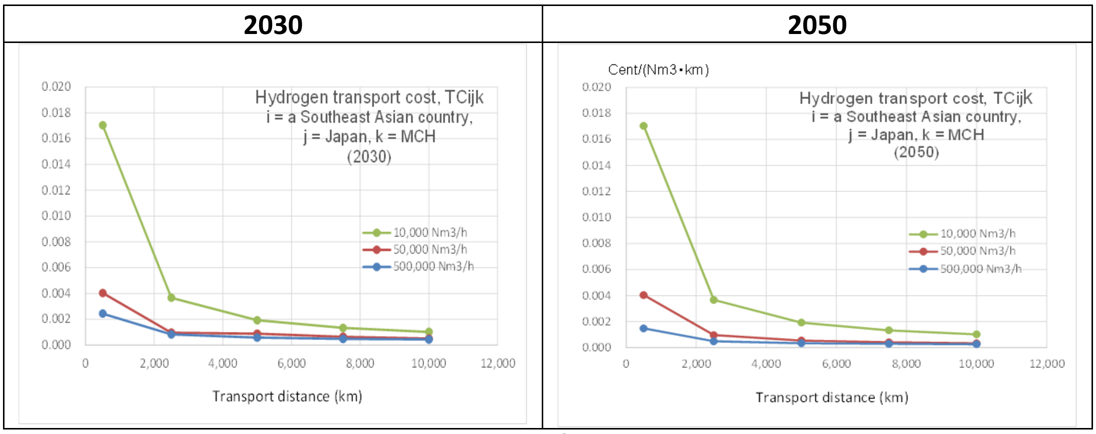
(i) The target years are 2030–2050.

(ii) The transport amounts of hydrogen are equivalent to 10,000 Nm^3/hour, 50,000 Nm^3/hour, and 500,000 Nm^3/hour.

(iii) Transport costs consist of overseas transport by ship – MCH by chemical tankers and liquefied hydrogen by liquid hydrogen ships.

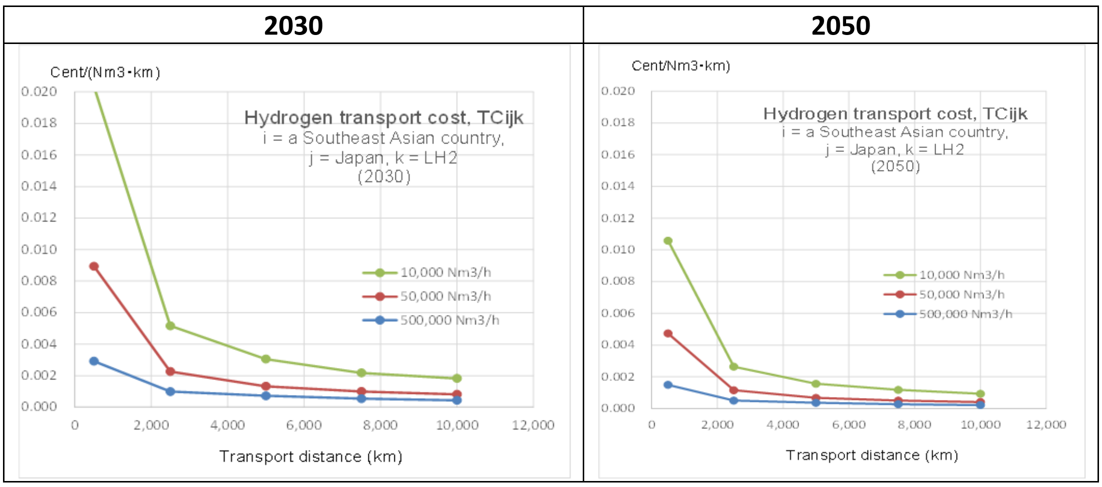
(iv) Distances are 500–10,000 km.

Figure 3.2. Unit Cost of Hydrogen Transport, Methylcyclohexane



h = hour, km = kilometre, MCH = methylcyclohexane, Nm^3 = normal cubic metre.
Source: Authors' calculations.

Figure 3.3. Unit Cost of Hydrogen Transport, Liquefied Hydrogen



h = hour, km = kilometre, L_2 = liquefied hydrogen, Nm^3 = normal cubic metre.
Source: Authors' calculations.

Hydrogen production costs depend on transport volume and distance. Liquefied hydrogen has an advantage due to its significant volume and long distances. However, small and mid-size hydrogen amounts over short and middle distances are more ideal with MCH.

Referring to Figures 3.2 and 3.3 and calculating an average between 2030 and 2050, the unit cost of hydrogen transport between shipping and receiving ports is defined in Table 3.4.

Table 3.4. Unit Cost of Hydrogen Transport between Shipping and Receiving Ports
(cent/Nm^3-km)

	Japan		Korea		Malaysia		Thailand		Singapore	
	MCH	**LH_2**	**MCH**	**LH_2**	**MCH**	**LH_2**	**MCH**	**LH_2**	**MCH**	**LH_2**
Australia	2.686403	2.201606	2.861701	2.142090	2.448077	2.173979	2.660423	2.203566	2.365271	2.149006
Brunei Darussalam	1.647809	1.766681	1.566005	1.661853	1.448334	1.476336	1.250556	1.299856	1.424133	1.450839
Malaysia	1.982898	2.023305	1.737338	1.876775	1.218762	1.238394	1.375224	1.420450	1.232574	1.252576
Indonesia	1.914345	1.988192	1.726893	1.869389	1.314300	1.372888	1.560495	1.655147	1.247912	1.263364
New Zealand	2.912273	2.103939	3.031016	1.946159	2.962180	2.052039	3.045239	1.917103	2.921226	2.0955795

km = kilometre, L_2 = liquefied hydrogen, MCH = methylcyclohexane, Nm^3 = normal cubic metre.
Source: Authors' calculations.

4. Results of Hydrogen Transport Optimisation Model

4.1. Optimisation of Hydrogen Transport Volume x Distance

First, using the hydrogen linear programming model, the following optimisation approach was conducted for the hydrogen volume x distance:

$$\sum_{i}\sum_{j}\sum_{k} \boldsymbol{X_{ijk}D_{ij}} \quad -> \boldsymbol{MIN} \tag{5}$$

Regarding the optimal calculation results, Australia and New Zealand will export their hydrogen mainly to Japan; Brunei Darussalam and Sarawak, Malaysia will export their hydrogen to neighbouring countries and areas such as Thailand and Peninsular Malaysia. Indonesia will export to Korea and Singapore. However, if Brunei Darussalam's hydrogen exporting amount increases by 1 billion Nm^3, it increases its hydrogen transport to Thailand by 1 billion Nm^3 (i.e. 26,979 to 27,979). Thus, Indonesia will decrease its hydrogen exports to Thailand and increase its exports to Singapore by 1 billion Nm^3; Australia will decrease exports to Singapore and increase exports to Japan; and New Zealand will reduce its exports to Japan by 1 billion Nm^3. As a result, Brunei Darussalam's objective function (i.e. the total transport amount x distance) will decrease 3% – the highest reduction amongst the five hydrogen-exporting countries. In this case study, Brunei Darussalam's hydrogen-exporting volume will be essential when an optimal hydrogen supply chain is sought in the EAS region (Tables 3.5 – 3.10)

Table 3.5. Optimal Hydrogen Transport Solution
(million Nm^3)

	Japan	Korea	Malaysia	Thailand	Singapore	Total Supply	Supply Constraint
Australia	279,984	0	0	0	4,329	284,313	284,313
Brunei Darussalam	0	0	0	26.979	0	26,979	26,979
Malaysia	0	0	106,474	22,193	0	128,667	128,667
Indonesia	0	193,609	0	5,616	10,378	209,603	209,603
New Zealand	22,827	0	0	0	0	22,827	22,828
Calculation	302,811	193,609	106,474	54,788	14,707	4,331,181,398	Volume x distance
Actual Demand	302,811	193,609	106,474	54,788	14,707	672,389	

Nm^3 = normal cubic metre.
Source: Authors' calculations.

Table 3.6. Australia's Increase of 1 Billion Nm^3 of Hydrogen Production
(million Nm^3)

	Japan	Korea	Malaysia	Thailand	Singapore	Total Supply	Supply Constraint
Australia	280,984	0	0	0	4,329	285,313	284,313
Brunei Darussalam	0	0	0	26,979	0	26,979	26,979
Malaysia	0	0	106,474	22,193	0	128,667	128,667
Indonesia	0	193,609	0	5,616	10,378	209,603	209,603
New Zealand	21,827	0	0	0	0	22,827	22,828
Calculation	302,811	193,609	106,474	54,788	14,707	4,329,464,498	Volume x distance
Actual Demand	302,811	193,609	106,474	54,788	14,707	672,389	

Nm^3 = normal cubic metre.
Note: The reduction ratio of the objective function compared to Table 3.5 is –0.04%.
Source: Authors' calculations.

Table 3.7. Brunei Darussalam's Increase of 1 Billion Nm^3 of Hydrogen Production
(million Nm^3)

	Japan	Korea	Malaysia	Thailand	Singapore	Total Supply	Supply Constraint
Australia	280,984	0	0	0	3,329	284,313	284,313
Brunei Darussalam	0	0	0	26,979	0	27,979	26,979
Malaysia	0	0	106,474	22,193	0	128,667	128,667
Indonesia	0	193,609	0	5,616	11,378	209,603	209,603
New Zealand	21,827	0	0	0	0	21,827	22,828
Calculation	302,811	193,609	106,474	54,788	14,707	4,198,216,893	Volume x distance
Actual Demand	302,811	193,609	106,474	54,788	14,707	672,389	

Nm^3 = normal cubic metre.
Note: The reduction ratio of the objective function compared to Table 3.5 is –3.10%.
Source: Authors' calculations.

Table 3.8. Sarawak, Malaysia's Increase of 1 Billion Nm^3 of Hydrogen Production
(million Nm^3)

	Japan	Korea	Malaysia	Thailand	Singapore	Total Supply	Supply Constraint
Australia	280,984	0	0	0	3,329	284,313	284,313
Brunei Darussalam	0	0	0	26,979	0	26,979	26,979
Malaysia	0	0	106,474	23,193	0	129,667	129,667
Indonesia	0	193,609	0	4,616	11,378	209,603	209,603
New Zealand	21,827	0	0	0	0	21,827	22,828
Calculation	302,811	193,609	106,474	54,788	14,707	4,322,354,698	Volume x distance
Actual Demand	302,811	193,609	106,474	54,788	14,707	672,389	

Nm^3 = normal cubic metre.
Note: The reduction ratio of the objective function compared to Table 3.5 is –0.20%.
Source: Authors' calculations.

Table 3.9. Indonesia's Increase of 1 Billion Nm^3 of Hydrogen Production
(million Nm^3)

	Japan	Korea	Malaysia	Thailand	Singapore	Total Supply	Supply Constraint
Australia	280,984	0	0	0	3,329	284,313	284,313
Brunei Darussalam	0	0	0	26,979	0	26,979	26,979
Malaysia	0	0	106,474	22,193	0	128,667	128,667
Indonesia	0	193,609	0	5,616	11,378	210,603	210,603
New Zealand	21,827	0	0	0	0	21,827	22,828
Calculation	302,811	193,609	106,474	54,788	14,707	4,323,865,898	Volume x distance
Actual Demand	302,811	193,609	106,474	54,788	14,707	672,389	

Nm^3 = normal cubic metre.
Note: The reduction ratio of the objective function compared to Table 3.5 is –0.17%.
Source: Authors' calculations.

Table 3.10. New Zealand's Increase of 1 Billion Nm^3 of Hydrogen Production
(million Nm^3)

	Japan	Korea	Malaysia	Thailand	Singapore	Total Supply	Supply Constraint
Australia	279,984	0	0	0	4,329	284,313	284,313
Brunei Darussalam	0	0	0	26,979	0	26,979	26,979
Malaysia	0	0	106,474	22,193	0	128,667	128,667
Indonesia	0	193,609	0	5,616	10,378	209,603	209,603
New Zealand	22,827	0	0	0	0	22,827	23,828
Calculation	302,811	193,609	106,474	54,788	14,707	4,331,181,398	Volume x distance
Actual Demand	302,811	193,609	106,474	54,788	14,707	672,389	

Nm^3 = normal cubic metre.
Note: The reduction ratio of the objective function compared to Table 3.5 is 0.00%.
Source: Authors' calculations

4.2. Optimisation of Hydrogen Transport Costs

If the optimal calculation results in regard to the transport mode of hydrogen are analysed, Australia exports its hydrogen to Japan through liquefied hydrogen, and Brunei Darussalam exports its hydrogen to Japan and Thailand by MCH. Sarawak, Malaysia exports its hydrogen to Peninsular Malaysia and Thailand by MCH. Indonesia exports to Korea, Peninsular Malaysia, and Singapore by MCH. New Zealand exports its hydrogen to Korea by liquefied hydrogen. Japan and Korea import hydrogen from Brunei Darussalam and Indonesia by MCH, but this can be replaced by liquefied hydrogen, because the cost difference is negligible.

A sensitivity analysis was then conducted in which each hydrogen-producing country increases its hydrogen production by 1 billion Nm^3. There is no effect for Australia, because hydrogen demand in Japan remains unchanged. Brunei Darussalam only increases its hydrogen exports to Japan by 1 billion Nm^3. Sarawak, Malaysia increases its hydrogen exports to Thailand by 1 billion Nm^3, altering Brunei Darussalam's exports by decreasing them to Thailand and increasing them to Japan.

A change in New Zealand's production brings more complicated changes to the hydrogen supply chain. This increases exports to Korea; as a result, Indonesia decreases exports to Korea and increases exports to Peninsular Malaysia. Sarawak, Malaysia thus decreases hydrogen transport to Peninsular Malaysia, thus increasing exports to Thailand. Finally, Brunei Darussalam's exports to Thailand decrease, but they increase to Japan. Regarding the impact to the reduction of the objective function, Brunei Darussalam has the highest at 0.05%, followed by Sarawak, Malaysia at 0.04% and Indonesia at 0.03%. Cost reduction effects are not significant.

Table 3.11. Optimal Solution of Transport Cost Model
(million Nm^3)

	Japan		Korea		Malaysia		Thailand		Singapore		Total Supply	Supply Constraint
	MCH	LH_2	MCH	LH_2	MCH	LH_2	MCH	LH_2	MCH	LH_2		
Australia	0	284,313	0	0	0	0	0	0	0	0	284,313	284,313
Brunei Darussalam	18,498	0	0	0	0	0	8,480	0	0	0	26,979	26,979
Malaysia	0	0	0	0	82,359	0	46,308	0	0	0	128,667	128,667
Indonesia	0	0	170,781	0	24,115	0	0	0	14,707	0	209,603	209,603
New Zealand	0	0	0	22,828	0	0	0	0	0	0	22,828	22,828
										Total Transport Cost	1,220,485	Total
Total Result	18,498	284,313	170,781	22,828	106,474	0	54,788	0	14,707	0	672,389	672,389
Total Demand		302,811		193,609		106,474		54,788		14,707	672,389	12,205

L_2 = liquefied hydrogen, MCH = methylcyclohexane, Nm^3 = normal cubic metre.
Source: Authors' calculations.

Table 3.12. Australia's Increase of 1 Billion Nm3 of Hydrogen Production

(million Nm^3)

	Japan		Korea		Malaysia		Thailand		Singapore		Total Supply	Supply Constraint
	MCH	LH_2	MCH	LH_2	MCH	LH_2	MCH	LH_2	MCH	LH_2		
Australia	0	284,313	0	0	0	0	0	0	0	0	284,313	285,313
Brunei Darussalam	18,498	0	0	0	0	0	8,480	0	0	0	26,979	26,979
Malaysia	0	0	0	0	82,359	0	46,308	0	0	0	128,667	128,667
Indonesia	0	0	170,781	0	24,115	0	0	0	14,707	0	209,603	209,603
New Zealand	0	0	0	22,828	0	0	0	0	0	0	22,828	22,828
										Total Transport Cost	1,220,485	Total
Total Result	18,498	284,313	170,781	22,828	106,474	0	54,788	0	14,707	0	672,389	673,389
Total Demand		302,811		193,609		106,474		54,788		14,707	672,389	12,205

L_2 = liquefied hydrogen, MCH = methylcyclohexane, Nm^3 = normal cubic metre.

Note: The reduction ratio of the objective function compared to Table 3.11 is –0.05%.

Source: Authors' calculations.

Table 3.13. Brunei Darussalam's Increase of 1 Billion Nm³ of Hydrogen Production

(million Nm³)

	Japan		Korea		Malaysia		Thailand		Singapore		Total Supply	Supply Constraint
	MCH	LH_2	MCH	LH_2	MCH	LH_2	MCH	LH_2	MCH	LH_2		
Australia	0	283,313	0	0	0	0	0	0	0	0	283,313	285,313
Brunei Darussalam	19,499	0	0	0	0	0	8,480	0	0	0	27,979	27,979
Malaysia	0	0	0	0	82,359	0	46,308	0	0	0	128,667	128,667
Indonesia	0	0	170,781	0	24,115	0	0	0	14,707	0	209,603	209,603
New Zealand	0	0	0	22,828	0	0	0	0	0	0	22,828	22,828
										Total Transport Cost	1,219,931	Total
Total Result	19,499	283,312	170,781	22,828	106,474	0	54,788	0	14,707	0	672,389	673,390
Total Demand		302,811		193,609		106,474		54,788		14,707	672,389	12,199

L_2 = liquefied hydrogen, MCH = methylcyclohexane, Nm³ = normal cubic metre.
Note: The reduction ratio of the objective function compared to Table 3.11 is –0.05%.
Source: Authors' calculations.

Table 3.14. Malaysia's Increase of 1 Billion Nm^3 of Hydrogen Production
(million Nm^3)

	Japan		Korea		Malaysia		Thailand		Singapore		Total Supply	Supply Constraint
	MCH	LH_2	MCH	LH_2	MCH	LH_2	MCH	LH_2	MCH	LH_2		
Australia	0	283,312	0	0	0	0	0	0	0	0	283,312	284,313
Brunei Darussalam	19,499	0	0	0	0	0	7,480	0	0	0	26,979	26,979
Malaysia	0	0	0	0	82,359	0	47,308	0	0	0	129,667	129,667
Indonesia	0	0	170,781	0	24,115	0	0	0	14,707	0	209,603	209,603
New Zealand	0	0	0	22,828	0	0	0	0	0	0	22,828	22,828
									Total Transport Cost		1,220,056	**Total**
Total Result	19,499	283,312	170,781	22,828	106,474	0	54,788	0	14,707	0	672,389	673,390
Total Demand		302,811		193,609		106,474		54,788		14,707	672,389	12,201

L_2 = liquefied hydrogen, MCH = methylcyclohexane, Nm^3 = normal cubic metre.
Note: The reduction ratio of the objective function compared to Table 3.11 is –0.04%.
Source: Authors' calculations.

Table 3.15. Indonesia's Increase of 1 Billion Nm^3 of Hydrogen Production

(million Nm^3)

	Japan		Korea		Malaysia		Thailand		Singapore		Total Supply	Supply Constraint
	MCH	**LH_2**	**MCH**	**LH_2**	**MCH**	**LH_2**	**MCH**	**LH_2**	**MCH**	**LH_2**		
Australia	0	283,312	0	0	0	0	0	0	0	0	283,312	284,313
Brunei Darussalam	19,499	0	0	0	0	0	7,480	0	0	0	26,979	26,979
Malaysia	0	0	0	0	81,359	0	47,308	0	0	0	128,667	128,667
Indonesia	0	0	170,781	0	25,115	0	0	0	14,707	0	210,603	210,603
New Zealand	0	0	0	22,828	0	0	0	0	0	0	22,828	22,828
										Total Transport Cost	1,220,152	Total
Total Result	19,499	283,312	170,781	22,828	106,474	0	54,788	0	14,707	0	672,389	673,390
Total Demand		302,811		193,609		106,474		54,788		14,707	672,389	12,202

L_2 = liquefied hydrogen, MCH = methylcyclohexane, Nm^3 = normal cubic metre.
Note: The reduction ratio of the objective function compared to Table 3.11 is –0.03%.
Source: Authors' calculations.

Table 3.16. New Zealand's Increase of 1 Billion Nm^3 of Hydrogen Production
(million Nm^3)

	Japan		Korea		Malaysia		Thailand		Singapore		Total Supply	Supply Constraint
	MCH	LH_2	MCH	LH_2	MCH	LH_2	MCH	LH_2	MCH	LH_2		
Australia	0	283,312	0	0	0	0	0	0	0	0	283,312	284,313
Brunei Darussalam	19,499	0	0	0	0	0	7,480	0	0	0	26,979	26,979
Malaysia	0	0	0	0	81,359	0	47,308	0	0	0	128,667	128,667
Indonesia	0	0	169,781	0	25,115	0	0	0	14,707	0	209,603	209,603
New Zealand	0	0	0	23,828	0	0	0	0	0	0	23,828	23,828
										Total Transport Cost	1,220,371	**Total**
Total Result	19,499	283,312	169,781	23,828	106,474	0	54,788	0	14,707	0	672,389	673,390
Total Demand		302,811		193,609		106,474		54,788		14,707	672,389	12,204

L_2 = liquefied hydrogen, MCH = methylcyclohexane, Nm^3 = normal cubic metre.
Note: The reduction ratio of the objective function compared to Table 3.11 is –0.01%.
Source: Authors' calculations.

5. Implications

Hydrogen is a future clean combustion fuel that can replace fossil fuels, which are used for heat and fuel demand in industry, transport, and power generation. However, hydrogen supply costs are currently expensive; these must be reduced through the expansion of hydrogen demand (i.e. scale merit). In addition, the development of innovative hydrogen production and transport technologies will help reduce hydrogen supply costs.

A hydrogen value chain – to connect both hydrogen production and demand sites – must be established. As mentioned, two hydrogen transport modes are available, MCH and liquefied hydrogen. Generally, MCH has an advantage in short and middle distances and small and mid-volumes. Yet liquefied hydrogen has advantages with middle to long distances and mid- to large volumes. The linear programming model shows similar results; if Australia and New Zealand transport their hydrogen to Japan and Korea, a hydrogen supply network can be established within ASEAN. Brunei Darussalam and Indonesia can still transport their hydrogen to Japan and Korea.

These results depend on assumed hydrogen transport costs, which are based on distance and volume. Appropriate hydrogen transport costs of both transport modes were assumed, but there were many uncertainties. Therefore, the hydrogen transport costs must be further examined to obtain more reliable numbers.

In addition, this study did not include hydrogen production costs before and after treatment of MCH and liquefied hydrogen, which are hydrogenation and dehydrogenation of MCH, and liquefaction and regasification of liquefied hydrogen.

Chapter 4

East Asia Summit Hydrogen Working Group Meetings

Most developed countries are committed to achieving carbon neutrality by 2050, but most ASEAN Members have set a target of 2060 or 2070. The first two phases of the hydrogen production potential study helped energy policymakers enhance their understanding of hydrogen technology, while this third phase focussed more on the role of hydrogen to support carbon neutrality in ASEAN+.

Due to the COVID-19 pandemic, ERIA and the Institute of Energy Economics, Japan (IEEJ) hosted two workshops virtually in March and June 2021. The first workshop discussed the role of hydrogen in achieving carbon neutrality towards 2050 within ASEAN, highlighting several best practices from selected EAS members. It published a press release to raise awareness of hydrogen's contribution to decarbonisation and to encourage regional cooperation on hydrogen usage in the region. The second workshop focussed on hydrogen's technology advancement and potential supply chain in the EAS region, followed by a progress report on hydrogen projects. Issues and challenges of hydrogen penetration from supply and demand sides were also discussed during roundtable sessions.

1. First Hydrogen Working Group Meeting, 23 March 2021

1.1. Japan's Hydrogen Policy and Strategy to Achieve Carbon Neutrality by 2050

Representatives from Japan's Ministry of Economy, Trade, and Industry presented Japan's hydrogen policy and strategy to achieve carbon neutrality by 2050. Ari Ugayama of the Hydrogen and Fuel Cell Strategy Office stated that Japan's policy – 'Hydrogen Society' – has embedded hydrogen into the basic economic plan, national strategy, and hydrogen road map. He said that hydrogen is a key contributor to decarbonisation, energy security, and industrial competitiveness. The Hydrogen Strategy is the first comprehensive national strategy to highlight hydrogen as a future energy option towards 2050 with the explicit goal of making hydrogen affordable. To realise this goal, three conditions must be met. On the supply side, low-cost feedstock and large-scale hydrogen supply chains are critical; on the demand side, mass applications, including power generation and industrial processes, are essential. Further, several technologies are being developed for hydrogen production, hydrogen transport, and fuel cell use.

The long-term target is to reduce hydrogen costs from $3 per kilogram in 2030 to $2 per kilogram by 2050. Hydrogen demand targets will be raised from 3 million tons per year by 2030 to around 20 million tons per year by 2050. Positioning hydrogen as a new resource in energy portfolio encourages a wide range players – and not only for mobility applications.

To expand the supply and demand of hydrogen, several actions have been taken in the context of hydrogen mobility applications, local/regional projects, international hydrogen supply chains, and power generation. To develop infrastructure, Japan established a joint venture, Japan H2 Mobility, in 2018 to develop hydrogen station networks. Furthermore, Japan also created hydrogen hubs in collaboration with various companies in different cities, and international collaboration to advance hydrogen technology has occurred through multiple pilot projects conducted with Brunei Darussalam and Australia. Lastly, the establishment of hydrogen power generation in the US, and stationary fuel cells for household and industrial use, show that the potential supply and demand of hydrogen will increase in the future.

1.2. How Will Hydrogen Contribute to Carbon Neutrality in the Future?

Shigeru Kimura, special advisor to the President on Energy Affairs, ERIA, stated that most countries in Europe and North America – and some in Asia – have set carbon-neutral targets by 2050 and have included hydrogen technology in their long-term energy policies. However, no ASEAN Members have any such targets. Under the business-as-usual scenario, share by energy source will be still dominated by fossil fuels (i.e. around 40%) with 20% going to renewable energy.

To set a carbon-neutral scenario for ASEAN, energy efficiency conservation should be promoted, and conventional renewable energy sources should be increased, such as hydro, geothermal, and biomass power generation. The region should also think about shifting from fossil fuels to new renewable energy, such as solar PV, wind, or nuclear power. Moreover, thermal power generation with CCUS should be used, and oil-based transport should be replaced with FCVs. These scenarios will be developed under the carbon neutral road map, with the specific goal of replacing coal and gas power generation with ammonia and hydrogen in 2030–2080 (with an increase in the mixing rate from 5% to 100%). When these carbon-neutral scenarios have been put into place, CO_2 emissions generated by fossil fuels can be reduced up to 90% under an alternative policy scenario by 2080.

1.3. Introduction of a Hydrogen Strategy

This session discussed policies, regulations, targets, technology transfer, value chains, and other related matters of hydrogen application from Australia, China, India, and New Zealand.

Australia's Policy and Hydrogen Status, James Hetherington, Hydrogen Strategy Team, Department of Industry, Science, Energy, and Resources, Government of Australia. Australia has very promising hydrogen production areas. Australia has vast resources to support not only a large-scale hydrogen industry but also large-scale renewable energy. In this case, renewable hydrogen and CCS hydrogen production can be supported.

In phase 1 of its strategy, Australia has set priorities to build foreign partnerships, advance technology demonstration, conduct groundwork, and obtain technology validation for hydrogen production. Phase 1 also covers supply chain testing and development and capacity enhancement to scale up to global markets.

The government is engaged in a variety of actions, including bilateral and multilateral collaborations, to strengthen supply chain linkages, shape markets, and foster investment. Work is currently being undertaken to examine regulatory barriers now in place, as well as the rules that must be changed to expand the hydrogen industry. In phase 2, from 2025, strategies will focus on large-scale market activation, identification of hydrogen market engagement, scaling up projects to support export and domestic needs through building partnerships, construction of Australian hydrogen supply chains, and creation of large-scale export industry infrastructure.

The next steps will focus on reducing the cost of hydrogen. A low-emission technology statement was released on a hydrogen initiative in Australia, emphasising the lower-emission future technology and low-emission trade. With advanced technology that has been identified, the focus now is to lower hydrogen cost to around $2, including in the production chain, making it more competitive. Building international partnerships is also highlighted; cooperation between Australia and Japan on a liquefied hydrogen supply chain would help accelerate uptake. Australia is, therefore, looking forward to advancing partnerships to support global hydrogen industry growth in the future.

Recent Policies and Status of Hydrogen Energy in China, Zheng Lyu, Carbon Data and Carbon Assessment Research Center, Shanghai Advanced Research Institute, Chinese Academy of Sciences. In 2020, the government announced new goals to boost the share of non-fossil fuels in primary energy consumption to 25% by 2030, as part of its intended nationally determined contributions to peak CO_2 emissions before 2030, and to achieve carbon neutrality before 2060. The transport sector will be the main target for fuel cell and hydrogen utilisation, although coal still contributes most of the CO_2 emissions. Recent national policies on hydrogen set demonstration application of FCVs, which will focus on heavy trucks. The demonstration application for city clusters should concentrate on three key areas: construction of a comprehensive industrial chain using FCVs, application of new FCV models and technologies, and establishment of a commercial operation model to strengthen the economy.

In the vehicle industry development plan for 2021–2035, several goals, including a research project on key technologies for new energy vehicles, support the commercial demonstration, industrialisation, and application of by-product hydrogen as well hydrogen production by renewable energy. In addition, the plan includes improving the standard system and management of hydrogen production, storage, transport, and refuelling infrastructure. In recent years, more than 40 provinces have released plans to promote FCVs and the hydrogen energy industry, including conducting research and development of key technologies on hydrogen production, storage, transport, fuel cells, and FCVs; developing an FCV industry chain; demonstrating application of fuel cell buses, trucks, and hydrogen-fuelling stations; and providing subsidies for purchasing FCVs as well constructing hydrogen-fuelling stations.

Currently, the annual hydrogen production in China is around 21 million tons. About 62% of hydrogen comes from coal, and 19% is from natural gas. Water electrolysis only accounts 1%, and rest is by-product hydrogen. By the end of 2020, cumulative sales of FCVs were more than 7,000, most of them buses or trucks, and 124 hydrogen-fuelling stations were built.

India’s Initiative towards Hydrogen Economy, Natarajan Rajalakshmi, Senior Scientist and Former Team Leader, Centre for Fuel Cell Technology, International Advanced Research Centre for Powder Metallurgy and New Materials, Telangana. Hydrogen is considered a potential answer to climate change and air pollution issues due to its storage, energy, and chemical properties. Currently, the cost of green hydrogen is declining, demand is expanding, and regulations to leverage hydrogen's benefits are being strengthened globally. Together with India's cheap and enormous untapped renewable resources potential, the country is an ideal location for green hydrogen generation.

India currently imports 38% of its energy – 30% of its coal, 85% of its oil, and 0% of its natural gas are imported. By utilising the green hydrogen generation capacity of domestic renewables, the country's import expenses can be greatly reduced. By 2050, India estimates that import costs may be cut by about $20 billion per year under an ambitious green hydrogen scenario.

Costs of green hydrogen generated from renewables are beginning to catch up with those of leading fossil fuel technologies, such as steam methane reformation, which utilises natural gas. Due to the high cost of grid electricity in India – particularly for industrial customers – off-grid configurations are more appealing. The high capital expenditures of CCUS, and the limited capacity of carbon storage sites, restrict hydrogen's role in fossil fuels to specific places.

Hydrogen deployment in various industries will take place across time and for a variety of reasons. By 2030, India intends to implement a comprehensive hydrogen system in refineries and steel mills. In terms of power, it is separated into two categories: short-term storage and seasonal storage, the latter of which will likely be dominated by hydrogen from the 2040s. Additionally, steel and ammonia will lead the development of high hydrogen consumption in the industrial sector, followed by refineries and methanol. Hydrogen is already employed in the manufacturing of ammonia, refineries, and methanol. Steel is projected to be the primary new development area within industry, as hydrogen can replace coal in the iron ore processing process.

FCVs’ total conversion efficiency (22%) is lower than that of battery electric vehicles (73%), suggesting that hydrogen will likely be reserved for certain modes of transport where electrification is not feasible. Hydrogen-fuelled vehicles could be used in conjunction with battery electric vehicles. Additionally, hydrogen's future significance in long-distance and heavy-duty applications are considerable.

India has committed to reduce greenhouse gas emissions by 35% below 2005 levels and to generate 40% of electricity from non-fossil fuel sources by 2030. Hydrogen has the potential to be a critical component in low-carbon energy systems. In terms of enhanced air quality and less dependency on imported fossil fuels, hydrogen-fuelled automobiles can complement battery electric vehicles in the transport industry. Hydrogen can assist industry in reducing emissions from operations that require input materials or feedstock produced from fossil fuels, such as the manufacturing of fertilisers, chemicals, petrochemicals, iron, and steel.

New Zealand Hydrogen Policy, Vidushi Challapali on behalf of Mark Pickup, Policy Advisor, Energy Market Policy, Energy and Resource Markets, Ministry of Business, Innovation and Employment, Government of New Zealand. New Zealand committed to 100% renewable electricity by 2030 and net-zero carbon emissions by 2050. New Zealand's hydrogen research and development have been established with the collaboration of several energy research institutes. The government already has legislated a target of decreasing all greenhouse gases, except for biogenic methane, to zero by 2050. New Zealand already had a highly renewable electricity mix in 2019, as 84% of its electricity generation came from its abundant hydro, wind, and geothermal resources. Yet relative reliance on hydropower means that there are challenges in ensuring the needs to manage interseasonal-year risk. In late 2020, an initiation was launched to consider the feasibility of pump hydro and other storage solution potential, including hydrogen-ensuring energy security.

New Zealand's energy sector is the largest contributor to national greenhouse gas emissions, and is therefore a priority. Green hydrogen made from renewable sources has a critical role to play in energy transition. 'A Vision for Hydrogen in New Zealand', published in 2019, is the first step in a hydrogen strategy. It outlined New Zealand's potential for hydrogen in the country, and some of the issues and barriers to its use.

Hydrogen is most likely to be used to decarbonise transport, particularly heavy transport and industrial processes. There is also significant potential for hydrogen export utilising New Zealand's renewable energy capacity. The next stage in the hydrogen strategy is a road map that will explore issues that need to be resolved in hydrogen use in the wider economy and what steps are necessary to resolve this. Work on the road map is expected to start in 1 year. It will consider a business-as-usual scenario to accelerate a deployment scenario, covering hydrogen demand and supply, capability, opportunities, effects on the electricity system and transport network, water requirements, and social licence. It will also consider legislation and regulations needed.

In the meantime, the hydrogen economy continues to grow. The Obayashi Corporation and Tuaropaki Trust have constructed a pilot hydrogen production facility, the first small green hydrogen production and refuelling facility at the port of Auckland. New Zealand has also funded several small and large hydrogen projects, including a study on hydrogen reticulation in the First Gas network, to enhance understanding on how hydrogen can be used and how the gas can be converted.

New Zealand has recently established a new national energy development centre to help lead the country's transition to a low-carbon future. The centre will help create new businesses and jobs, while helping the country move towards clean, affordable renewable energy. Local studies have also highlighted the value of hydrogen in New Zealand, including a First Gas study, post-aluminium smelter hydrogen, and a green freight strategy.

New Zealand has been active in research on hydrogen. The government research institute, Scion, is pursuing options for utilisation of biomass and hydrogen by thermal processing. Another government research institute, GNS Science, has projects on fuel cells, eco-friendly hydrogen production, and electrocatalytic energy production and storage. In addition, a project under the Ministry of Business, Innovation, and Employment and the German Federal Ministry of Education and Research supports green hydrogen research. The New Zealand Hydrogen Council is also collaborating with various German research institutes.

1.4. Hydrogen Strategies of Selected ASEAN Members

Overview of Hydrogen Opportunities for Brunei Darussalam, Shaikh Mohamad Faiz Shaikh Hj Fadilah, Special Duties Officer Grade II, Renewable Energy Unit, Sustainable Energy Division, Ministry of Energy, Government of Brunei Darussalam. Brunei Darussalam is working with Japan on the Advanced Hydrogen Energy Chain Association for Technology Development demonstration project, which will test the international transport of MCH. Under this project, hydrogen is created by steam reforming natural gas, then it is shipped to Japan in ISO containers. NEDO is funding this study.

In the energy value chain flow, since the idea is to replace oil and gas, the value chain of fossil fuels must be considered as well. Regarding oil, which is primarily used for transport, from the point of supply to delivery, 15% can be estimated as lost.

Hydrogen utilisation options in Brunei Darussalam have been discovered, including those related to power generation, FCVs, and renewables. Co-firing with natural gas is used to generate electricity at a pre-existing 30% efficiency. FCVs can be used as an alternative to electric vehicles for low-carbon vehicle deployment. However, charging electric vehicles is less expensive than hydrogen fuel cells. Renewable hydrogen enables the utilisation of excess renewable energy generation and requires a carrier to maintain stability and transport. Because this possibility will require additional investment and infrastructure in comparison to the country's pre-existing energy system, a compelling economic case is required to convince stakeholders.

Brunei Darussalam needs to dig deeper into its resource availability for both blue and green hydrogen. As a way forward, the country can start to formulate a strategy and policy to enable hydrogen industry development. As a historically energy export-oriented country, it is recommended that the main priority be to assess export opportunities. The export industry would facilitate in-country use of hydrogen, as Brunei Darussalam is currently focussing on diversification and growth of its economy. New business opportunities can provide the means to fund in-country hydrogen use.

Current Status and Prospect of Hydrogen Development in Indonesia, Saleh Abdurrahman, Senior Advisor to the Minister for Environment and Spatial Planning, Secretariat General, Public Bureau, Ministry of Energy and Mineral Resources, Government of Indonesia. Indonesia's 2017 national energy general plan established a renewable energy target of 31%

by 2050 and a commitment to reduce greenhouse gas emissions by 29% by 2030. Indonesia is optimistic about developing hydrogen, because the country has significant reserves of blue and green hydrogen as well as untapped gas resources. Furthermore, geothermal resources in Indonesia can be utilised as renewable green hydrogen sources.

The development of hydrogen in Indonesia is being studied by research institutions in partnership with state-owned companies and international institutions. Furthermore, HDF Energy and independent power producers completed a preliminary study on hybrid green hydrogen with solar PV and wind power in East Nusa Tenggara. PT Pertamina Geothermal Energy has also begun a pilot project to produce green hydrogen using geothermal energy.

Papua has untapped potential for hydropower, but the electricity consumption is low there due to its low population. Through the ERIA hydrogen concept plan, this potential can be exploited in the future. The plan is to build a hydroelectric plant in Papua to generate hydrogen and to convey it to more densely populated areas (e.g. Java, Bali, and Sumatra). This could also be a way to enhance development in Papua.

Demand and Supply Potential of Hydrogen Energy in Malaysia, Muhamad Izham Abd Shukor, Principal Assistant Secretary, Electricity Policy and Planning Division, Ministry of Energy and Natural Resources, Government of Malaysia. Since 2006, Malaysia has had solar, hydrogen, and fuel cell road maps. In 2020, it set a target for 31% renewable energy in 2025 and 40% in 2035, as well as 45% emissions reduction by 2030 from the 2005 level. Hydrogen is part of future, as stated in 12th Malaysia Plan 2021, although it is still in a research and development stage.

Regarding Malaysia's electrical profile, gas accounts for around 42% of capacity in 2019, followed by coal (32%), renewables (22%), and other sources (4%). Coal has the biggest share of the generation mix (42%), followed by gas (39%), and large-scale hydro (17%). Malaysia's power planning is guided by the energy trilemma principle (i.e. energy security, affordability, and sustainability). Hydrogen may be considered if it meets specific criteria and produces a balanced output in accordance with this principle.

Malaysia's most recent power development includes Peninsular Malaysia electricity plans, which meet 80% of the country's electricity demand. A battery energy storage system, with a total capacity of 500 MW, will be introduced under this strategy between 2030 and 2034. Additionally, renewable energy and natural gas will gradually phase out coal, and the new power generation development plan anticipates the retirement of approximately 7,000 MW of coal by 2033.

Hydrogen is seen as an opportunity for economic growth in Malaysia. On the business side, Petronas is driving hydrogen projects, and the company is committed to net-zero emissions by 2050. It has signed many memoranda of understanding to realise this commitment. In addition, Petronas established its hydrogen business in October 2020 and is actively seeking customers.

Sarawak will be the first state in Malaysia with an integrated hydrogen production plant. The federal government believes that Malaysia needs to balance planning based on the energy trilemma principle, but Sarawak has a different perspective, given that it has great hydropower capacity. Sarawak will be ready to produce hydrogen fuel for export by 2023 with the completion of a large-scale production facility in Bintulu with the capacity to produce 1,000 tons per year in the first few years, which can be scaled up to 10,000 tons per year in the future.

There is a possibility of hydrogen application in transport due to the country currently working on low-carbon mobility targets. Electric vehicles are the main choice for the government to push forward, and FCVs are seen as the last mile in reducing emissions. Malaysia can also explore its energy storage potential, such as battery storage. By 2030, if hydrogen technology can be competitive enough for other types of storage, Malaysia will choose hydrogen.

Updates on Hydrogen Technology Development in Thailand, Twarath Sutabutr, Chief Inspector General, Ministry of Energy, Government of Thailand. Thailand is a hydrogen-producing country, as hydrogen is produced as a by-product from refineries and gas plants. The country also has a pilot project using hydrogen with hydrolysis technology. Thailand's National Energy Plan is focussed on it becoming a net-zero carbon-neutral country. CCUS is the priority.

Thailand has also formed an alliance of major players in hydrogen technology, the Thailand Hydrogen Alliance. Toyota, PTT, and Bangkok Industrial Gas have carried out collaborative research with the aim of implementing a pilot project to identify the entire supply chain from petrochemical by-products to renewable energy to maximise industry benefits and to boost FCVs in the transport sector. The goal is to provide a technological rationale for putting hydrogen onto the road map, having incentives and policies in place, and verifying the operation of FCVs and hydrogen infrastructure, which is expected to make Thailand a net-zero country in the future.

2. Second Hydrogen Working Group Meeting, 10 June 2021

2.1. Forecast of Hydrogen Production Potential Based on Unused Energy in the East Asia Summit Region

Kutani Ichiro, IEEJ, presented the potential of hydrogen production based on unused energy in the EAS region. He stated that the fundamentals of hydrogen production can be elaborated by two types of feedstock employed: hydrocarbon and water. Three types of unused energies were chosen as feedstock in this study: lignite coal, flared gas, and untapped hydropower potential.

Lignite coal is not being used at the time, despite the fact that there is sufficient lignite reserves. Commercialisation rates were assumed to be 75% of available resources (high) and 25% of available resources (low). The hydrogen output from coal was assumed to be 21 tons of lignite to produce 1 ton of hydrogen. In EAS countries such as Indonesia, it was assumed that two-thirds of lignite was reserved in Kalimantan and one-third in Sumatra. In Japan and

Myanmar, the reserves were shown to be insufficient to sustain hydrogen production for years. In the Lao PDR, no reserves for hydrogen production remains.

To utilise CCS hydrogen, it is necessary to assess the possible capacity of the ground to hold CO_2 emissions. Although no data were available for each country, Table 4.1 contains data for Australia, China, and India.

Table 4.1. Carbon Dioxide Emissions from Lignite and Potential of Carbon Capture and Storage, Selected Countries

		Australia	China	India
Carbon content of lignite	kg/GJ	27.6	27.6	27.6
Lignite consumption for producing hydrogen	million tons	56,299	2,496	2,718
Net caloric value of coal	kJ/kg	9,800	10,000	9,546
CO_2 emissions from lignite	Gton-CO_2	56.0	2.5	2.6
Potential of Carbon Capture and Storage				
Sub-Commercial	Gton-CO_2	43.60	105.00	0.84
Undiscovered	Gton-CO_2	360.30	3,067.00	63.30

CO_2 = carbon dioxide, Gton = gigaton kg = kilogram, kJ = kilojoule.
Source: IEEJ estimation based on IEA (2020) and Pale Blue Dot Energy (2020).

The availability of flared gas validates the reserve–production ratio of oil reserves, which is used to determine whether a country can sustain crude oil output and thus gas flaring in 2040. A country with a reserve–production ratio of less than 5 years will be unable to maintain oil production beyond 2040. For the assumption of hydrogen output from natural gas, the transformation efficiency is 70% (i.e. using GCV/GCV basis). In certain EAS countries, such as New Zealand and Thailand, crude oil production has ceased, resulting in no gas flaring in 2040. In Indonesia, 25% of oil production is estimated to be in Kalimantan, 50% in Sumatra, and 25% on Java.

Final untapped hydroelectric feedstock indicated hydropower capacity expansion up to 2040 under specified policy and sustainable development scenarios, with new development beginning in 2018. Similar to lignite coal, commercialisation rates were assumed to be 75% of available resources (high) and 25% of available resources (low). Hydrogen production from electricity was assumed to be 5 kilowatts per ton of hydrogen, with a conversion efficiency of 70% (i.e. GCV basis).

In conclusion, lignite coal has the greatest potential for use as a hydrogen source. Australia has the greatest potential for production, followed by New Zealand and Indonesia. Hydrogen production potential from conventionally unused energies was negligible in comparison to hydrogen demand potential. Solar PV and wind energy generation have the potential to increase production. Additionally, hydrogen produced from lignite and hydropower has the advantage of having a controllable output.

2.2. Optimisation of the Hydrogen Supply Chain in the East Asia Summit Region

ERIA and the ASIAM Research Institute produced a study on the optimisation of the hydrogen supply chain in the EAS region. Shigeru Kimura, ERIA and Hiruma Takahisa, ASIAM Research Institute explained that hydrogen is an innovative energy technology that will help the EAS region achieve carbon neutrality in the future. Hydrogen will be traded amongst countries in the EAS region, from those that export it to those that import it.

ERIA examined optimal solutions for hydrogen trade in the EAS region in 2040 using the linear programming method. Australia, Brunei Darussalam, Indonesia, Malaysia (Sarawak State), and New Zealand represented the hydrogen-supply countries in the region, while Japan, Korea, Malaysia (Peninsular), Singapore, and Thailand were the hydrogen-demand countries. MCH and liquefied hydrogen represented the two methods of transporting hydrogen.

In terms of hydrogen demand in 2040, hydrogen supply will consist entirely of hydrogen production from unused energy. The forecast placed a premium on the balance of hydrogen supply and demand. Total demand was adjusted for each hydrogen-producing country based on the forecast for hydrogen production. As a result, total hydrogen production was equal to total hydrogen demand. The costs of hydrogen transport were tentatively forecasted for both MCH and liquid hydrogen under a variety of assumptions. They must be refined as hydrogen transport technology advances.

In conclusion, MCH is effective over a short distance, while liquefied hydrogen is extremely competitive over a long distance. For intermediate distances, both modes of transport are nearly identical. An advantage of a liquefied hydrogen ship is that it produces no CO_2. As a result, chemical tankers will be required to switch from conventional fuel oil to zero-emission fuels such as hydrogen or ammonia.

With a cruising range of 5,000–6,000 km, liquefied hydrogen was recommended if hydrogen demand is high; however, if hydrogen demand is moderate and small, MCH was recommended due to tanker operations. Brunei Darussalam, Indonesia, Malaysia, and New Zealand could be critical points for hydrogen supply. The transport costs for MCH and liquefied hydrogen used in this study were provisional, as there is considerable uncertainty in the future; thus, this result is still in the test stage. However, the characteristics of both modes of transport are readily apparent.

2.3 Hydrogen Gas Turbine – Practice from Mitsubishi Heavy Industries

Tanimura Satoshi, a representative of Mitsubishi Heavy Industries, announced that Mitsubishi has set a goal of helping achieve a net-zero carbon society by 2050. Mitsubishi's strategy is to increase efficiency and the use of hydrogen and ammonia as fuels, as well as to increase the capacity of existing facilities and to use battery energy storage systems to support renewable energy systems. Its road map outlines a strategy for reducing CO_2 emissions, which includes efficiency improvements, modernisation of existing facilities, use of energy storage, CO_2 recovery, and fuel conversion, such as the development of hydrogen gas turbines. Additionally, Mitsubishi Power is increasing its portfolio of carbon-free power generation options. Around 30% hydrogen co-firing has already been achieved, and by 2025, it is predicted to reach 100%.

Mitsubishi has advanced technology development by utilising the most advantageous hydrogen combustion technologies available. Hydrogen gas turbines have a number of environmental and economic benefits, including that they require minimal investment, act as a catalyst for infrastructure expansion and cost reduction, are carrier-agnostic, and operate in a flexible manner. Mitsubishi Power offers three types of combustion technology to meet the needs of individual projects and hydrogen density targets: diffusion (Type 1) with a target of 100% hydrogen density, pre-mix (DLN, Type 2) with a target of 30% hydrogen density, and multi-cluster (DLN, Type 3) with a target of 100% hydrogen density.

In 2021, Mitsubishi Power commenced development of the world's first ammonia-fired 40 MW-class gas turbine system with the target to expand the line-up of carbon-free power generation options with commercialisation around 2025. Mitsubishi Power's hydrogen gas turbine projects are located mostly in the US, Europe, South Australia, and Singapore.

Mitsubishi Power's approach to a hydrogen society is to expand the scope of activities, including strategic partnerships; develop a market for green hydrogen and ammonia; participate in front-end engineering design activities; and pursue business feasibility studies in the run-up to commercialisation.

2.4 Progress Reports of Hydrogen Projects

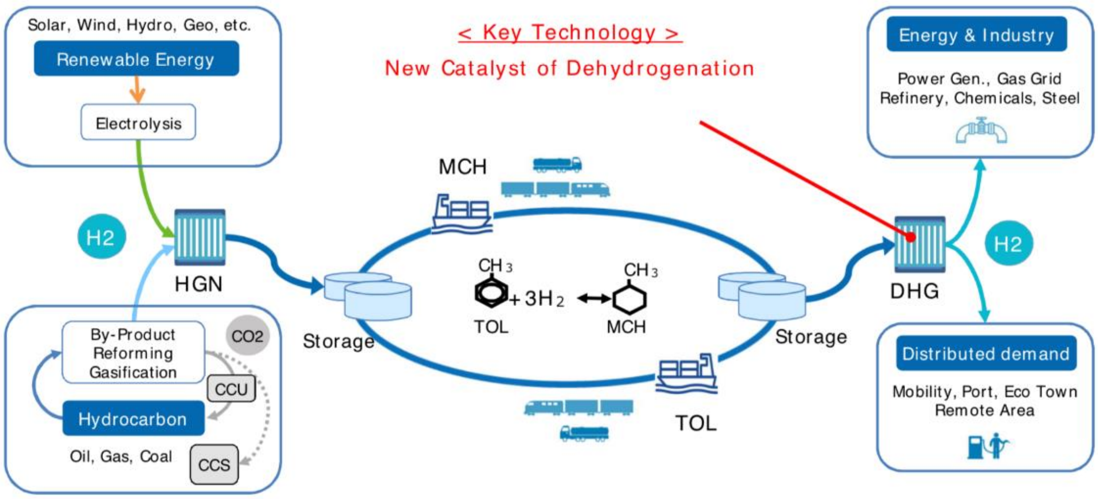
Fukushima Hydrogen Energy Research Field (FH2R) Project in Japan, Hara Daishu, Advanced Battery and Hydrogen, Technology Department, NEDO. NEDO, Toshiba Energy Systems and Solutions Corporation, Tohoku Electric Power, and Iwatani Corporation announced that the FH2R, which had been under construction in Namie, Fukushima Prefecture since 2018, has been built with a renewable energy-powered 10 MW-class hydrogen production unit, the largest class in the world, at the end of February. It began operations in March 2020, after a nearly 2-year development phase.

The FH2R is a 10 MW alkaline electrolysis system capable of producing up to 1,200 Nm^3 of hydrogen per hour (rated power operation) utilising renewable energy. Additionally, the hydrogen produced at the FH2R will be used to power stationary hydrogen fuel cell systems and to fuel mobility devices such as fuel cell automobiles and buses. FH2R serves as a research lab for future hydrogen by examining how green hydrogen can be used to manage and optimise electrical power fluctuation. To that goal, extensive management systems have been developed to control devices such as electrolysers, solar PV-producing facilities, and hydrogen storage units.

SPERA Hydrogen Pilot Project in Brunei Darussalam, Ikeda Osamu, Hydrogen Business Department, Chiyoda Corporation. Chiyoda Corporation is attempting to diversify its business portfolio into greener and new industries such as hydrogen. The hydrogen supply chain is a component of Chiyoda's mid-term growth strategy, which includes expansion into the technology and service sectors.

The company's energy coverage under the energy transformation strategy is divided into three distinct areas: hydrogen, CCSU, and new utility. At the moment, the primary focus of hydrogen research is on MCH, although ammonia and liquefied hydrogen are also included. Chiyoda is also expanding its CCSU business, which includes syngas, para-xylene, ethylene (electrosynthesis), and concrete material. For new utilities, energy management (e.g. balancing and low-carbon) and microgrids (e.g. resilience and low-carbon) are also covered.

Figure 4.1. Methylcyclohexane Hydrogen Supply Chain



Source: Chiyoda Corporation.

Figure 4.1 represents hydrogen production and hydrogen demand using MCH. Energy is in industry, as are distributed demands such as mobility, ports, eco-towns, and remote areas. When hydrogen gas is poured into water electrolysis using renewable energy or fossil fuels, hydrogen gas is converted to liquid using toluene as the hydrogen carrier. For toluene, the hydrogen reacts and converts to MCH and then is transported to the demand side. The hydrogen will extract hydrogen gas and change the toluene back into hydrogen so that the toluene will be recycled. This is a hydrogen transport mechanism using MCH. Almost all technologies are proven, but dehydrogenation is the challenge.

Key features of MCH hydrogen technology are (i) its chemical stability, as it has only minor MCH loss during long-term storage and long-distance transport; (ii) its ease of handling, as the liquid remains liquid under ambient temperatures and pressure (i.e. 1/500 in volume); (iii) liquid that can be utilised by existing infrastructure, standards, and regulations to minimise social investment for hydrogen introduction; (iv) its safe storage and transport, which means liquids can be managed as petroleum products; and (v) almost all technology is a combination of conventional and new technology.

In MCH technology development phase 1, Chiyoda developed a dehydrogenation catalyst in 2008 that achieved optimum performance over 12,000 hours of continuous operation. Meanwhile, under phase 2, Chiyoda confirmed the performance and long life of the catalyst through 10,000 hours of continuous operation of its pilot plant from April 2013 to November 2014. Under phase 3, Chiyoda and partners established the Advanced Hydrogen Energy Chain Association for Technology Development and initiated the world's first global hydrogen supply chain demonstration project. In this phase, Chiyoda transported a vehicle from Brunei Darussalam to Japan – around 5,000 km overseas. A maximum scale of 210 tons per year of hydrogen has since been transported. The project is supported by the Government of Japan, and Chiyoda operates this supply chain.

The SPREA hydrogen network is enlarging the supply chain to deliver hydrogen to Japan, storing hydrogen as a form of MCH for delivery to a decentralised city, and working as a large-scale storage hub.

Hydrogen Energy Supply Chain Pilot Project, Fukuma Yuko, Project Section 2, Project Department, Project Group, Hydrogen Strategy Division, Kawasaki Heavy Industries. Kawasaki Heavy Industries has fertiliser plants, liquefied hydrogen storage tanks, liquefied hydrogen containers, and hydrogen gas turbines. By applying these technologies, it is leading entry into the hydrogen energy supply chain.

Utilisation of large volumes of hydrogen is essential for decarbonisation. Renewable energy-only energy systems and battery storage have limits on energy scale, facility costs, and applications. Liquid hydrogen enables the transport and storage of large, long-lasting energy, and connects various sectors. With a very wide range of industries involved in the hydrogen supply chain and demand field, hydrogen has been highlighted as creating a cycle that is good for the environment and economy. Kawasaki Heavy Industries is contributing to decarbonisation, as it is the only company to own an entire hydrogen supply chain technology from production, transport, and storage, to utilisation.

Hydrogen can be produced from a variety of sources and countries. Hydrogen also allows for large-scale, long-distance, long-term energy delivery and storage, as well as sector integration, which contributes to resilience. Furthermore, future energy is affected by the movement of liquid hydrogen carriers. Kawasaki Heavy Industries can deliver renewable energy throughout the world using liquid hydrogen. It allows hydrogen to be produced not just from fossil fuels combined with CCUS, but also from renewable energy sources. Kawasaki Heavy Industries is also in discussions with many stakeholders to realise the hydrogen supply chain.

The concept of a CO_2-free hydrogen supply chain promoted by Kawasaki Heavy Industries is to provide a stable energy supply while reducing emissions. The supply chain is undertaking a pilot project between Australia and Japan with many partner companies using hydrogen brought to Japan as liquid hydrogen. This supply chain is very similar to the energy supply chain. The difference between natural gas and hydrogen is that hydrogen is a secondary energy and can be produced from many resources, but natural gas is one of the most promising resources for large-volume hydrogen reduction. Kawasaki Heavy Industries believes this large-scale supply chain will accelerate the realisation of decarbonisation and a sustainable future.

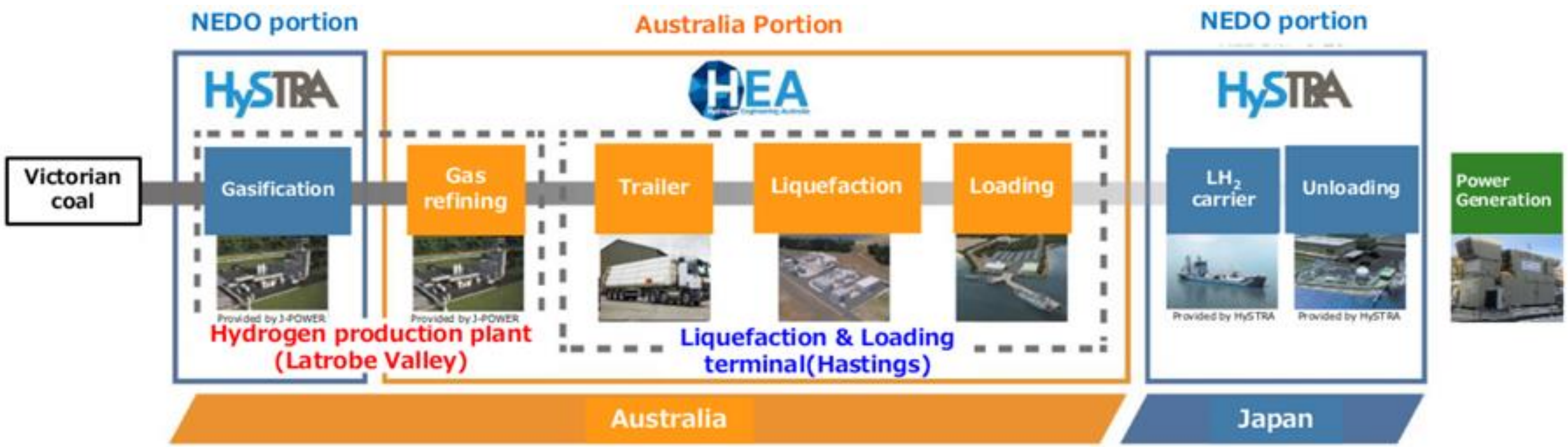
As a mass transport mechanism for hydrogen, Kawasaki Heavy Industries has chosen transport by melting hydrogen. By liquefying hydrogen, the volume of gas in atmospheric form can be lowered to 1/800. As a result, it can be transported in large quantities – efficiently. In terms of characteristics, liquid hydrogen has a high purity, requiring no refinement, and may be delivered to fuel cells via evaporation alone. Hydrogen is also non-toxic, odourless, and has no greenhouse effect. It is harmless if discharged into the atmosphere in an emergency, which is a significant benefit. The mass transport of hydrogen can be realised by integrating this storage technique with energy carrier technology.

Figure 4.2. Well-to-Tank Carbon Dioxide Emissions
(per normal cubic metre liquid hydrogen)

CCS = carbon capture and storage, H2 = hydrogen, PV = photovoltaic.
Source: Kawasaki Heavy Industries.

Some may be concerned about CO_2 emissions if fossil fuels are used. Figure 4.2 shows the well-to-tank CO_2 emissions from each hydrogen production method (i.e. renewables or lignite). In the case of lignite, carbon capture and storage will be required. CO_2 emissions from liquid hydrogen made by lignite carbon capture and storage will be the same as other productions made by renewable energy. This is critical information in terms of lignite usage.

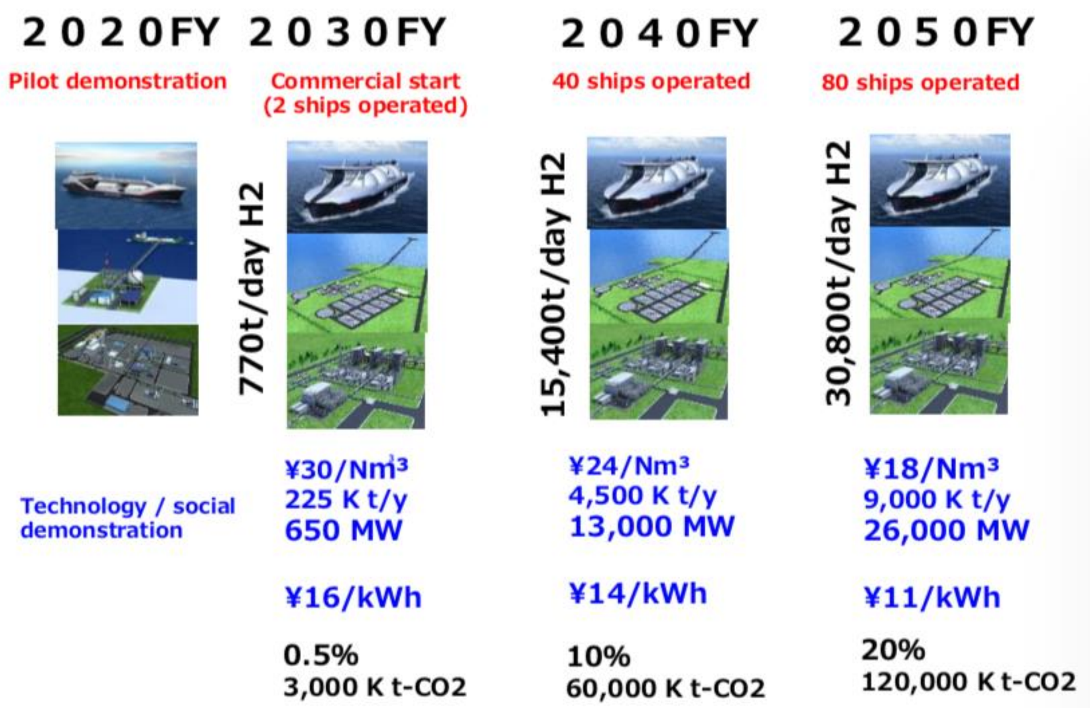
Figure 4.3. Pilot Demonstration Structure between Australia and Japan



Source: Kawasaki Heavy Industries.

Kawasaki Heavy Industries is working with several partners on the pilot project supported by the governments of Japan and Australia. Figure 4.3 shows the two portions of pilot demonstration: NEDO and Australia. The scope of the NEDO portion is liquefied hydrogen carriers and unloading in Japan, and it is supported by the Ministry of Economy, Trade, and Industry and HySTRA. In Australia, the scope is gas refining in the loading terminal, and it is supported by the Government of Australia performed by Hydrogen Engineering Australia.

Figure 4.4. Share of Power Generation Carbon Dioxide Reduction Forecast



CO_2 = carbon dioxide, FY = fiscal year, H2 = hydrogen, Kt = kiloton, kWh = kilowatt-hour, NW = megawatt, Nm^3 = normal cubic metre, y = year
Source: Kawasaki Heavy Industries.

Through the relationship between energy demand and cost reduction, it is possible to further reduce hydrogen costs in the future. Figure 4.4 depicts a commercial hydrogen business starting in 2030 and increasing demand in 2050. Carbon pricing or government assistance is not considered, so it is likely that costs will be reduced further. In the future, when commercialisation is widespread, the cost of hydrogen power generation can be competitive with that of fossil fuel.

Hydrogen from fossil fuels linked to CCUS will realise a broad, affordable energy supply that will contribute to energy security. No CO_2 emissions occur – only water is emitted – which will realise clean energy. In addition, hydrogen will realise an energy supply that will contribute to energy security, and widespread use will lead to industrial growth, including increased infrastructure export deployment as well as future sustainability.

In conclusion, Kawasaki Heavy Industries emphasised the importance of the CO_2 hydrogen supply chain to achieve decarbonisation. Hydrogen from fossil fuel resources such as natural gas and coal with CCUS relies on both energy supplies. This contributes to the proper supply and security of energy. In addition, the use of hydrogen emits less CO_2, so hydrogen is expected to play a low role in decarbonisation. The widespread use of hydrogen will lead to industrial and economic growth. Hydrogen production began with fossil fuels and will eventually convert to renewable energy in the future, which has the potential to create a sustainable energy society.

2.5 Country Updates from ASEAN+ Representatives on Issues and Challenges of Supply and Demand in Hydrogen's Penetration

Roundtable discussions were conducted on issues and challenges in hydrogen penetration, particularly supply and demand. Seven countries took part, including four ASEAN Members (i.e. Brunei Darussalam, Indonesia, Malaysia, and Thailand), China, India, and New Zealand. The discussion is summarised in Table 4.2.

Table 4.2. Country Updates from ASEAN+ Representatives

Country	Updates
Brunei Darussalam	The country supports hydrogen utilisation and is exploring green hydrogen opportunities. Per the Petroleum Authority, it is looking to grey and blue hydrogen using solar PV.
China	Utilisation of hydrogen is expanding, as more local governments have announced plans to develop hydrogen. The government set a target to utilise 10,000 FCVs by 2025. Furthermore, several companies have plans to build around 5,000 hydrogen-fuelling stations by 2025. Around 42%–60% of emissions come from steel productions. Some companies are attempting to use hydrogen for ship fuel and for the steel industry. Hydrogen is also used by automotive manufacturers as well as construction sectors. As power generation is still highly dependent on fossil fuels, hydrogen can substitute for coal power plants in the future.
India	For the past 3–6 months, India has greatly progressed on hydrogen technology. The government is planning to initiate green hydrogen development by generating 30 GW of electrolysis plant capacity. This initiation will be started in the refinery, fertiliser, and steel industries. For electricity generated by both solar PV and wind, the country plans to locate refineries close to solar PV and wind sources to reduce the costs of electricity.
Indonesia	It is setting up hydrogen policy; green hydrogen is part of a long-term strategy for climate resilience to be developed by 2035. Indonesia will concentrate on green hydrogen for the power sector, as well as blue hydrogen from coal (lignite). Indonesia may still use coal by 2050 with down-streaming hydrogen. Pertamina, the state-owned oil and gas company, is continuing its research on hydrogen, and is collaborating with Japan, Australia, and New Zealand on geothermal power plants with electrolysis methods to produce hydrogen. In consideration of carbon

Country	Updates
	pricing, Indonesia has just launched the new cap and trade initiative for power generation. It has begun to examine the carbon market and its price for relevant companies. Stakeholders can only sell the credit domestically.
Malaysia	The science academy in Malaysia presented a hydrogen road map to the Ministry of Economy to promote hydrogen use. Malaysia's economic planning unit is looking into the implementation of hydrogen, and the country is still waiting on a hydrogen policy. Malaysia held a climate action council meeting on carbon pricing, and the Ministry of Environment is exploring carbon pricing. Malaysia has similar issues to Indonesia regarding carbon trading limitations.
New Zealand	Several hydrogen pilot projects are operational. Demand for hydrogen use is evident in the transport sector, port infrastructure, and industry sectors such as urea plants. Several small-scale hydrogen production pilot projects have been launched as well, but the primary one is a joint venture between Japan's Obayashi Corporation and Tuaropaki Trust. Numerous well-funded local and international organisations are currently searching for large-scale green hydrogen development in New Zealand. Several of these projects focus on an area called Taranaki in the middle of the North Island in an offshore gas field. They are either repurposing existing offshore gas platforms for wind turbines or developing new floating wind turbines. In the south, an electricity smelter is scheduled to close in 2024, producing approximately 800 MW of renewable energy. There is emphasis on companies that believe in green hydrogen production as well. In terms of policy and regulation, New Zealand published a hydrogen policy in 2019 that was largely educational in nature. New Zealand intends to develop a road map outlining the optimal pathway and expected volume of hydrogen production in the country. Additionally, the country will determine the optimal level of the government involvement in private sector development, investment in New Zealand's self-sufficient hydrogen nation, or in a hydrogen exporter. Meanwhile, the government has concentrated its efforts on identifying regulatory impediments to hydrogen development. In terms of hydrogen economics, New Zealand can produce hydrogen at a cost-competitive rate using renewable energy. In terms of hydrogen transport technology, New Zealand should be an exporting nation, potentially be small exporter on liquid hydrogen or MCH, it will inevitably need to follow the major market
Thailand	Thailand has a working group composed of public and private sector organisations, including PTT and Toyota, which conducts hydrogen pilot projects and monitors a variety of issues, including regulation and safety. The country's policy framework places a premium on electric vehicles. Hydrogen will play a role in automobile applications as well as in stationary energy storage. Thailand also has a few pilot projects that convert excess electricity from wind farms to hydrogen; another is a household-level pilot project. Additional research is required, and a policy framework should be established in the near future.

FCV = fuel cell vehicle, GW = gigawatt, MCH = methylcyclohexane, MW = megawatt, PV = photovoltaic.

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Appendices

Appendix 1

Workshop on the Hydrogen Potential Study of Demand and Supply Sides
ERIA-IEEJ-India Hydrogen Meeting
Virtual Workshop – 25 June, 2021

The Economic Research Institute for ASEAN and East Asia (ERIA) and the Institute of Energy Economics, Japan (IEEJ) hosted a virtual workshop on 25 June 2021 on a study of the demand and supply of hydrogen. The objectives were to emphasise the importance of hydrogen as source of energy, coexisting with fossil fuels, growing renewable energy, and greater sustainability. Institutions from India that attended this workshop included representatives from the Automotive Research Association of India; Bhaba Atomic Research Center; Bharat Heavy Electricals; Central Electro Chemical Research Institute; Department of Science and Technology, Government of India; Indian Institute of Science; International Advanced Research Centre for Powder Metallurgy and New Materials; Malaviya National Institute of Technology Jaipur; Ministry of New and Renewable Energy, Government of India; Oil and Natural Gas Corporation; The Energy and Resources Institute; and some private companies that have interests in hydrogen technology.

In the opening remarks, R. Gopalan, regional director, International Advanced Research Centre for Powder Metallurgy and New Materials, pointed out that hydrogen is the most powerful and flexible energy carrier. It can be used to store, move, and deliver energy. The hydrogen fuel cell can play a major role in national energy strategy due to its potential for oil and gas applications across many sectors, such as transport and power. Due to its high efficiency on net-zero emissions, hydrogen and fuel cells have the potential to reduce greenhouse gas emissions. In India, fertilisers and petroleum refinery industries use hydrogen on a large scale based on the steam-reforming process. Hydrogen is also produced using water electrolysis on a small scale for on-site applications in India. Rural industries in India also produce hydrogen as a by-product. Depending on the natural process of hydrogen, grey, blue, and green hydrogen can be obtained, and there is more focus in India to produce green and blue hydrogen due to its ability to achieve net-zero carbon emissions.

In the 2021 budget, the Government of India announced a comprehensive national hydrogen programme, which aims to produce hydrogen from green resources. Other funding, such as from the Department of Science and Technology, Ministry of New and Renewable Energy, and Centre for Science and Environment, encourages national laboratories, economic institutes, and industries to take up major research on the growing hydrogen demand in the country. Industry, such as oil corporations, natural gas corporations, Hindustan petroleum corporations, GAIL, and natural thermal cooperation, are also playing a vital role in hydrogen demand. Moreover, The Energy and Resources Institute provides reports on the potential role of hydrogen.

Hydrogen will play a major role in sustainable energy in the coming years. There are numerous global challenges, such as hydrogen energy realisation, transport, storage, and durability.

The following are materials presented by ERIA, IEEJ, Chiyoda Corporation, and Kawasaki Heavy Industries during this workshop.

1. Session 1: Introduction of the Hydrogen Potential Study by ERIA

Contents

- EAS Energy Outlook of India
  - Econometrics approach
- Net Zero Emissions
- Net Zero Emissions of India
- Why Hydrogen?
- Current Trends of Hydrogen
  - National Hydrogen Strategy by Japan
  - Hydrogen Ministerial Meeting
- Scope of Work in 2018-19 Phase 1
- Scope of work in 2019-20 Phase 2

EAS Energy Outlook of India (Macro Assumptions)

Economic Growth
5.7 % P.A. from 2017 to 2050

Population Growth
0.6 % P.A. from 2017 to 2050
1.339 billion persons in 2015 to increase to 1.64 billion in 2050

GDP per capita
1,980 thousand US$/person (constant 2010 price and US$) in 2017 increases to 9,950 thousand US$/person in 2050

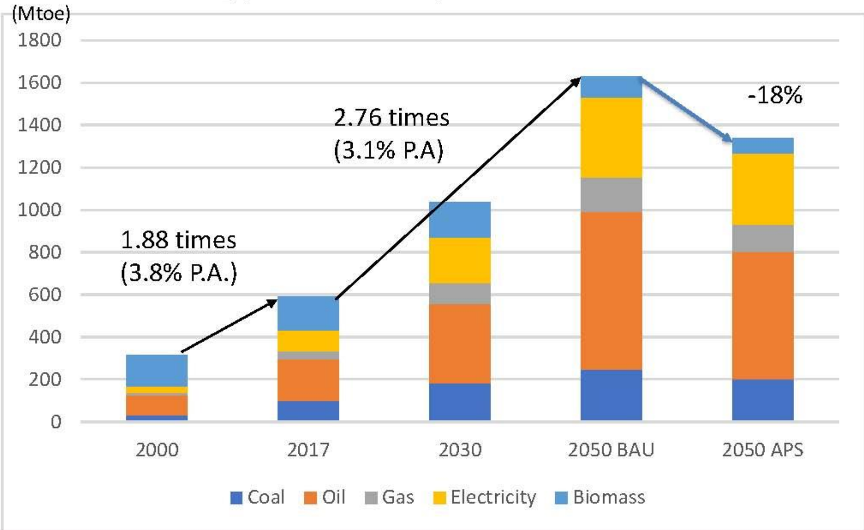
Crude Oil Price (nominal price)
Increase to about 250 US$/bbl in 2050 due to future tight balance between demand and supply

Source: ERIA ESP WG Report 2019-20

3

EAS Energy Outlook Result of India

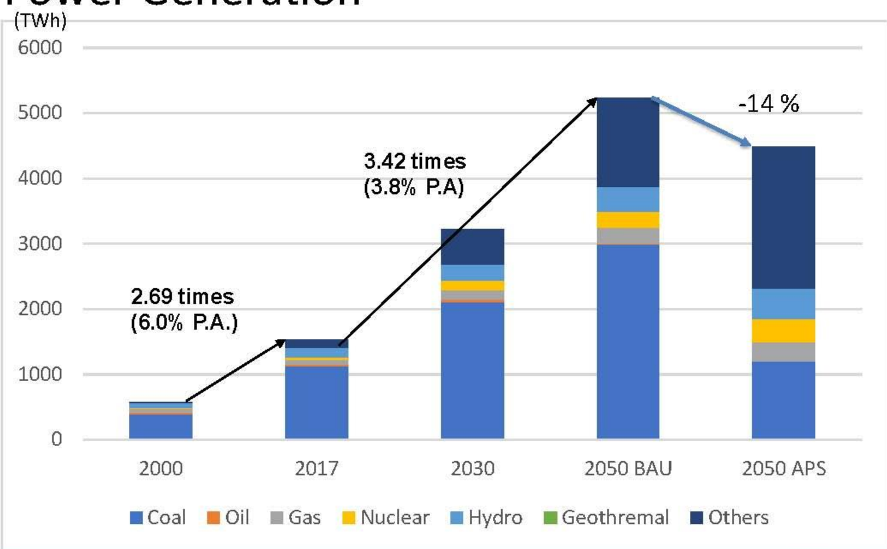
- Final Energy Consumption



Source: ERIA ESP WG Report 2019-20

EAS Energy Outlook Result of India

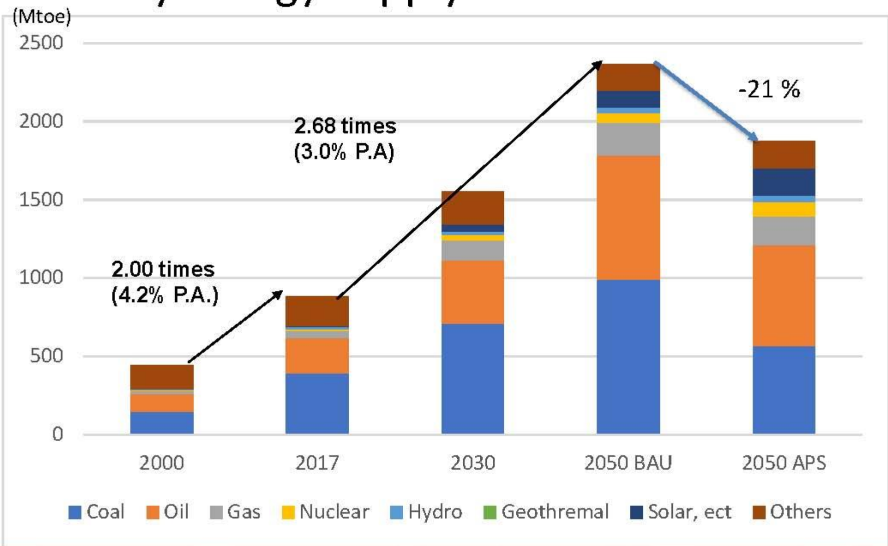
- Power Generation



Source: ERIA ESP WG Report 2019-20

EAS Energy Outlook Result of India

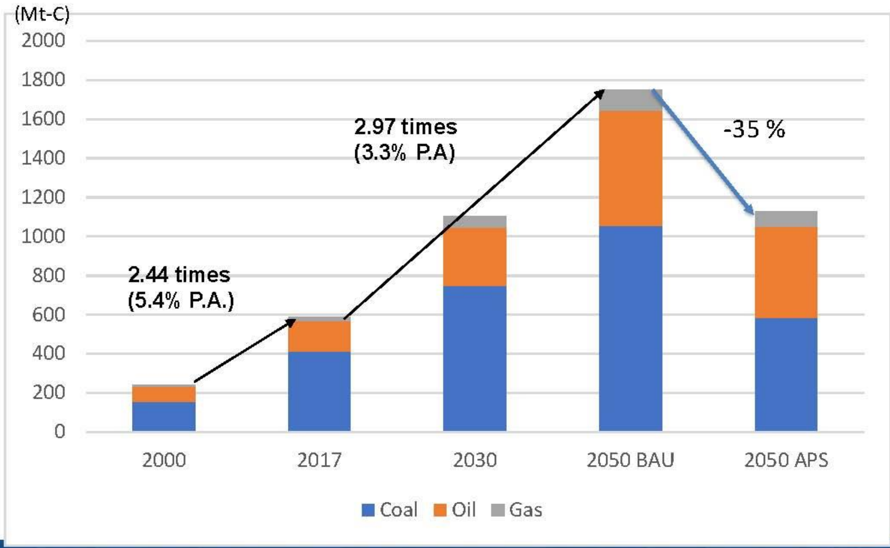
- Primary Energy Supply



Source: ERIA ESP WG Report 2019-20

EAS Energy Outlook Result of India

- CO2 Emissions



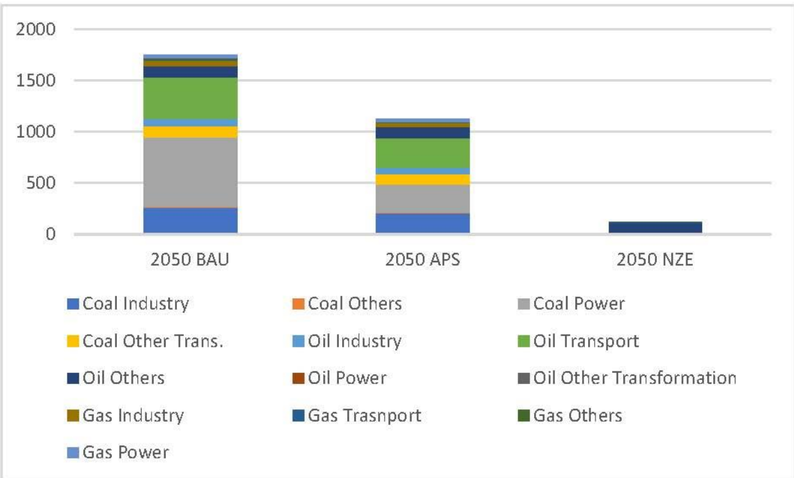
Source: ERIA ESP WG Report 2019-20

Net Zero Emissions

- Many countries especially in Europe, North America and Asia regions announce Net Zero Emissions targets;
  - European countries, Canada, US, Japan and South Korea: 2050
  - China:2060
  - Singapore: beyond 2050
- ERIA has been supporting ASEAN countries to prepare their net zero emission scenarios applying an optimization approach
  - Select zero emission energy technologies under cost minimum objective (liner programming)

ERIA

Net Zero Emission of India



Hydrogen: Gas Power, Gas Industry and Oil Transport
Ammonia: Coal Power and Oil Industry
CCUS: Coal Industry and Coal Other Transformation
Issue: Oil Others (LPG)

ERIA

WHY HYDROGEN ?

- Hydrogen will be an important source of energy, coexisting with current fossil fuels and growing renewable energy, for greater sustainability of our planet in future.
- The challenge is how to make hydrogen economically viable, financially attractive, and socially beneficial.

1. ZERO CO2 EMISSIONS

Hydrogen bonds with oxygen to generate electricity/heat, with water the only by-product.

2. UNLIMITED SUPPLY

Hydrogen can be extracted from a wide range of substances including oil, natural gas, biofuels, sewage sludge, and can be produced from unlimited natural energy by the electrolysis of water.

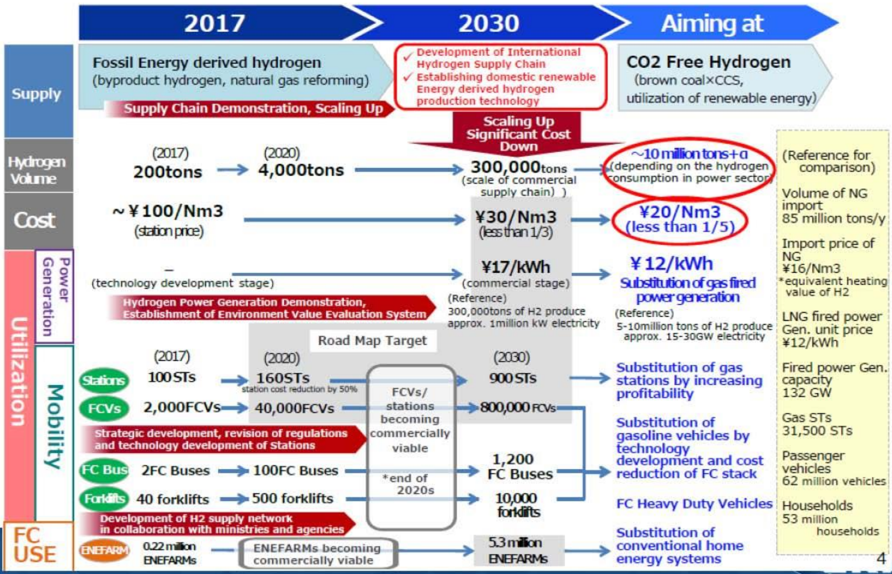
3. STORAGE AND TRANSPORTATION

Hydrogen is able to store energy beyond the seasons (from summer to winter) and transport for long distance (from south to north), to effectively utilize distributed natural energy and fossil fuels in the planet.

10

JAPAN's POLICY - Basic Hydrogen Strategy

- The Japanese Government decided on the "Basic Hydrogen Strategy (December, 2017)" to show the plan of action until 2030, the future vision in 2050.



(Source) METI "The Basic Hydrogen Strategy"

11

Current Trends of Hydrogen: 1st Hydrogen Ministerial Meeting in 2018

Scope of Work of Hydrogen Potential Study Phase 1

- Review of renewable energy policies including hydrogen of EAS countries
- Forecasting of hydrogen demand potential of EAS countries except Russia and US
- Forecasting of hydrogen supply potential and cost
- Well to wheel analysis
- Country survey
  - Indonesia, Malaysia, Thailand
  - Australia, India, New Zealand
- Lecture workshop in Indonesia
- Studied in 2018-19

Scope of Work of Hydrogen Potential Study Phase 2

- Review of Hydrogen Production and Supply Cost by **IEEJ**
- Review of Hydrogen Demand Potentials by **IEEJ**
  - Fuel for power generation
  - Fuel for FCV and FC train
  - Fuel for industrial use e.g. Heating boiler
- Review of hydrogen transport cost and its perspective (MCH) by **Chiyoda** Corporation
- Review of hydrogen transport cost and its perspective (LH2) by **KHI** Corporation
- EAS Hydrogen Working Group meeting
- Lecture Workshop in Thailand and Brunei Darussalam
- Studies in 2019-20

ERIA

Thank you for your attention!!

ERIA

2. Session 2: Hydrogen Production and Supply Cost by IEEJ

ERIA/ARCI Workshop, June 2021

Hydrogen production and supply cost

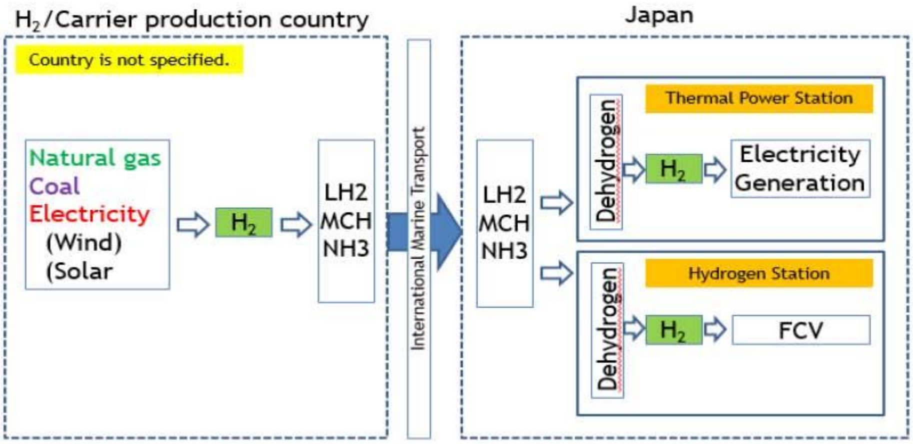
Ichiro KUTANI

Strategy research unit

The Institute of Energy Economics, Japan

Case study of Japan's H_2 import

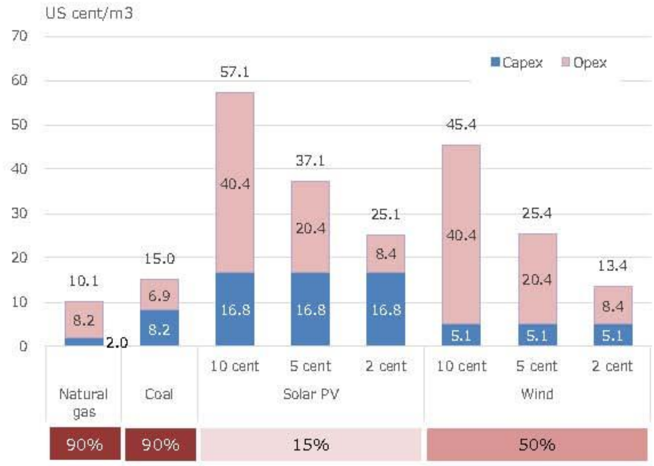
- NEDO conducted the hydrogen cost study from 2014 to 2017.
- The study assumed Japan will import hydrogen and consume it as a fuel for power generation or vehicle.



FCV = fuel-cell vehicle, LH2 = liquified hydrogen, MCH = Methylcyclohexane, NH3 = ammonia
Source: ERIA (2020)

H_2 production

- It resulted that steam reforming of natural gas is the lowest cost technology to produce commercial scale hydrogen.
- Cost of feedstock and capacity factor of a plant affect much.



Capacity factor of a plant

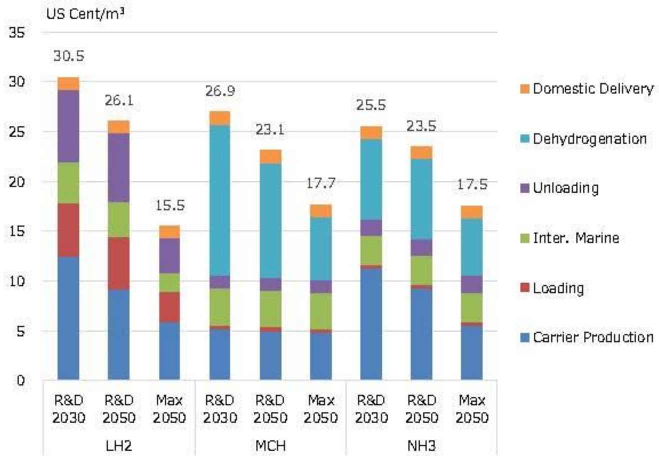
Cost of producing hydrogen

Natural gas price = $5/MMBtu
Coal price = not disclosed
Electricity price for water electrolysis = 10 cent/5 cent/2 cent
Source: ERIA (2020)

2

H_2 for power 1

- Economics of scale affect much on delivery cost.
  - When the demand is smaller, NH_3 can be the lowest cost option.
  - When the demand become greater, LH_2 can be the lowest cost option.



Cost of delivering hydrogen

LN2 = liquified hydrogen
MCH = Methylcyclohexane
NH3 = ammonia
Source: ERIA (2020)

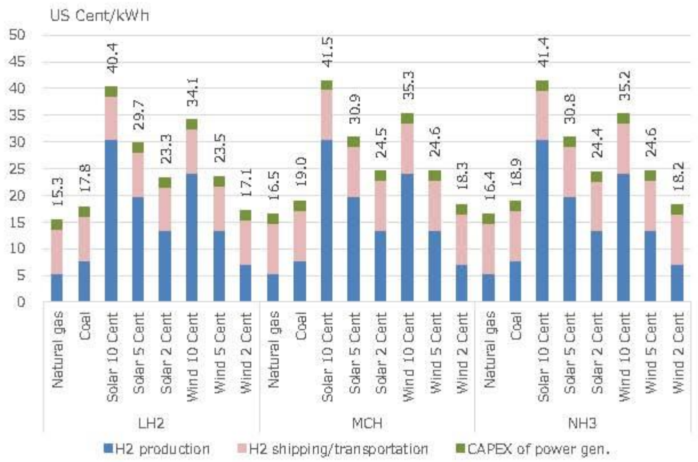
Hydrogen demand scenario

R&D 2030	Advance in R&D will reduce the cost of hydrogen in 2030, thereby initiating hydrogen demand.
R&D 2050	Advance in R&D will further reduce the cost of hydrogen in 2050, thereby stimulating hydrogen demand.
Max 2050	Competitive hydrogen cost will maximize hydrogen demand.

3

H_2 for power 2

- Hydrogen production cost determine total cost, while CAPEX of power plant has marginal effect.
- Shipping/transportation cost will not be negligible in the future of increasing hydrogen demand.



Cost of generation electricity from hydrogen CCGT

Electricity price for household is approx. US cent 25/kWh in Japan.

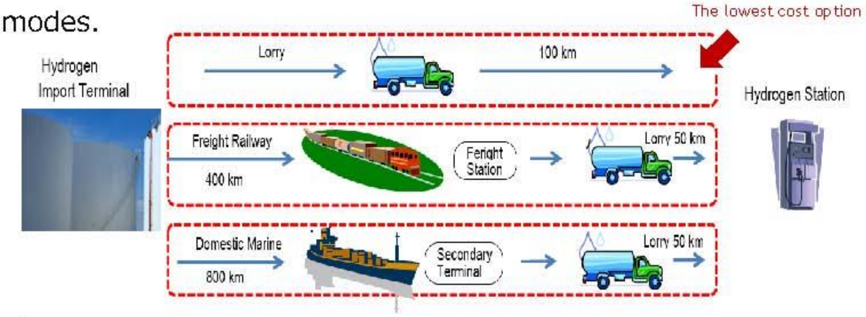
LCOE of thermal power generation is approx. US cent 8-10/kWh in Japan.

Demand = Max2050 scenario

LN2 = liquified hydrogen
MCH = Methylcyclohexane
NH3 = ammonia
Source: ERIA (2020)

H2 for vehicle 1

- 3 delivery modes.



- 3 demand sizes.

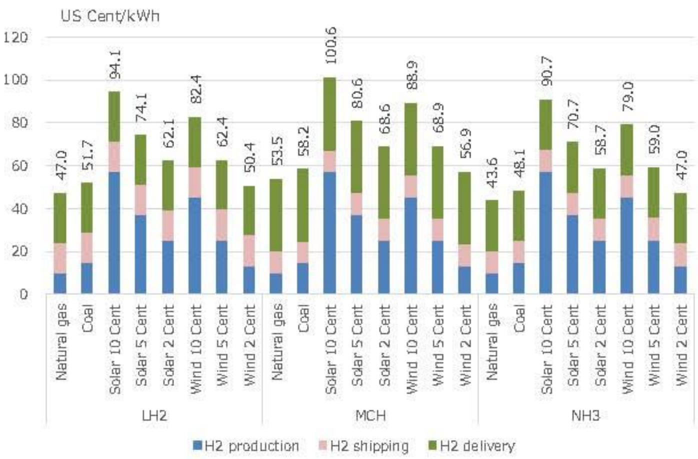
The lowest cost option

	Scenario		
	Small	Medium	Large
Hydrogen sales	300 Nm³/h	Ave. 830 Nm³/h Max. 1,200 Nm³/h	Ave. 1,240 Nm³/h Max. 2,400 Nm³/h
(Gasoline sales equivalent)	(100 KL/month)	(200 KL/month)	(300 KL/month)
Number of visitors (Peak hour)	8 vehicles/h 2 dispensers	15 vehicles/h 3 dispensers	22 vehicles/h 4 dispensers
Number of visitors (Monthly)	4,000 vehicles	8,000 vehicles	12,000 vehicles

H_2 for vehicle 2

- Hydrogen delivery cost (*) has significant impact in many cases.

* Delivery cost = transporting hydrogen carrier from the hydrogen import terminal to the hydrogen station, storing it, reproducing hydrogen from the carrier, and sending it to dispenser.



Hydrogen supply cost at a dispenser

Delivery mode = 100km by a lorry tank
Demand = Large scenario

LN2 = liquified hydrogen
MCH = Methylcyclohexane
NH3 = ammonia
Source: ERIA (2020)

Gasoline price ≒ US cent 14/kWh
Diesel price ≒ US cent 10/kWh
in Japan.

Fuel economy of FCEV is approx. 1.8 times better than ICE vehicle.

Conclusion

- Imported hydrogen is expensive compared to existing energies.
- Hydrogen can be a competitive fuel for power generation if a country can produce it in the country.
- Technological break through to reduce delivery cost is needed to make hydrogen an economical choice for vehicle fuel.
- Further reduction of production cost and shipping cost is needed to create hydrogen market.
- Policies help create a virtuous cycle of increasing demand and reducing costs.

Thank you!

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We provide part of our cutting-edge research results on energy and the environment on our website free of charge.

IEEJ Website
http://eneken.ieej.or.jp/

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IEA 2020b	IEA, World Energy Outlook 2020
IEA 2020c	IEA, CO2 emission from fuel combustion 2020
Iseki 2012	ISEKI Takaya, Membrane Reformer for Energy Efficient Hydrogen Production, 2012
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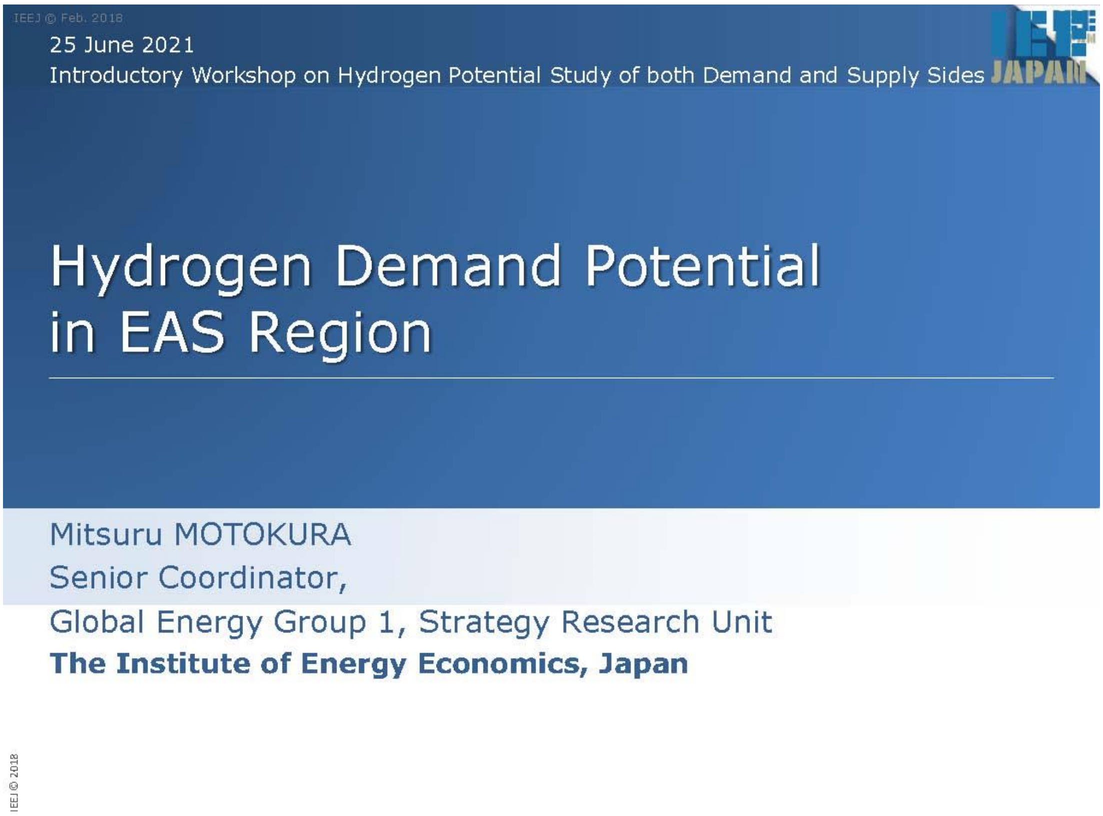
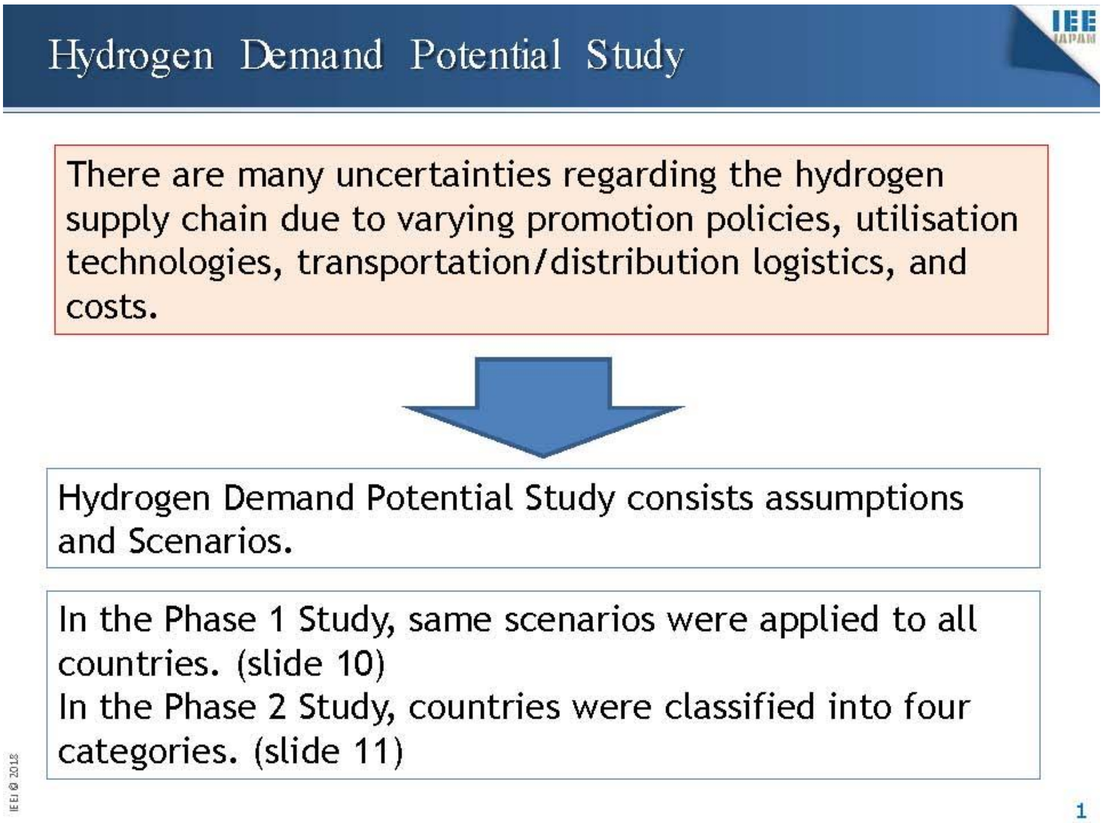
World Bank 2021	The World Bank, Global Gas Flaring Reduction Partnership, access in May 2021

3. Session 3: Hydrogen Demand Potential in the East Asia Summit Region by IEEJ





Basic assumption

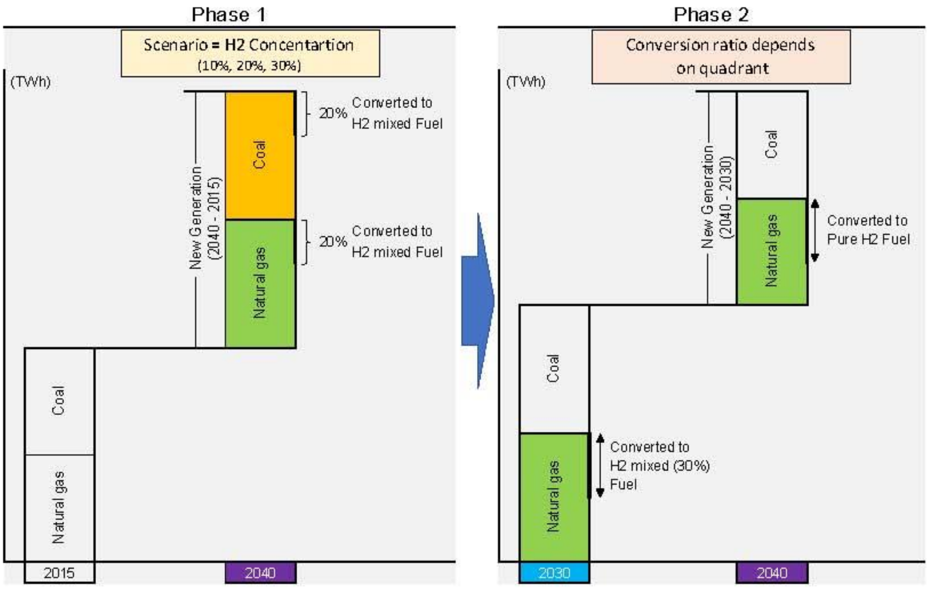
- Nation wide H_2 **pipeline** is only partially established in 2040 as well as H_2 **refueling stations.**
- Ammonia, which is hydrogen carrier, for combustion purpose is excluded in this study as well as hydrogen for generating ammonia and/or methanol.
- Commercialized and prevailed H_2 technologies in 2040
  - H_2 and Natural gas mixed fuel gas turbine
  - H_2 and natural gas mixed fuel large scale boiler
  - Passenger Fuel Cell Vehicle (PFCV)
  - Fuel Cell Bus (FCB)
  - Fuel Cell Train (FCT)

Not prevailed technology in 2040
- Utility scale FC
- FC-Heavy-Duty-Vehicle
- FC-Ship (Technically available, but international and domestic refueling infrastructures will only be partially established in 2040.)

Note: Distributed FC system is not included in this study, because hydrogen would not be supplied directly unless hydrogen pipeline will be realized. Hydrogen for distributed FC system would be produced from on-site natural gas reforming, thus fuel demand for distributed FC system is categorized to “natural gas demand”.

Scenarios (Phase 1 and Phase 2)

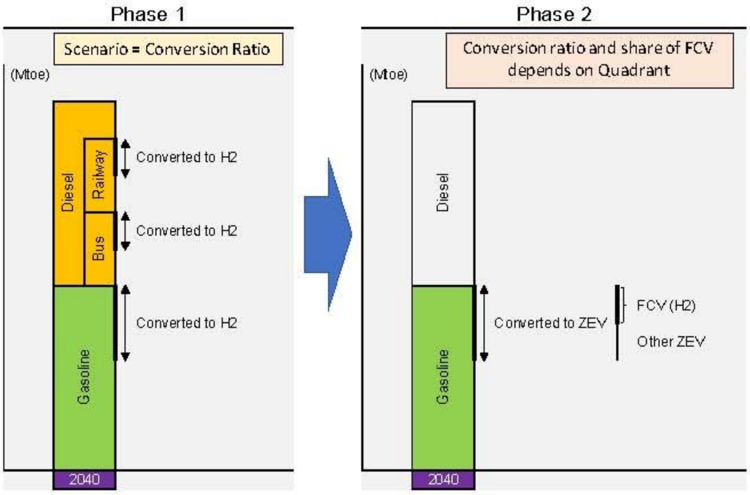
Sector: Electricity Generation



Note; Coal was excluded in the Phase 2 Study.

Scenarios (Phase 1 and Phase 2)

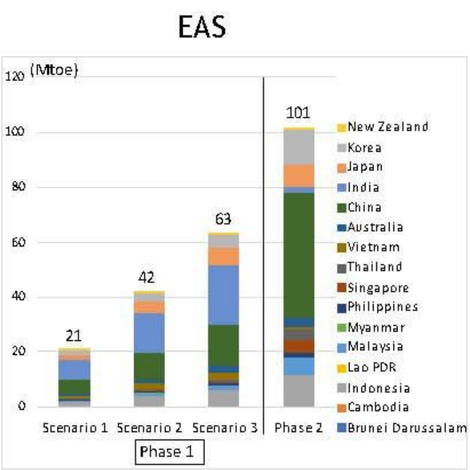
Sector: Transport

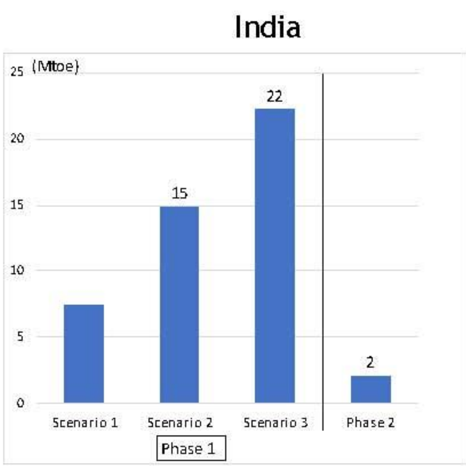


Note; Diesel was excluded in the Phase 2 Study.

Hydrogen Demand Potential

Sector: Electricity Generation

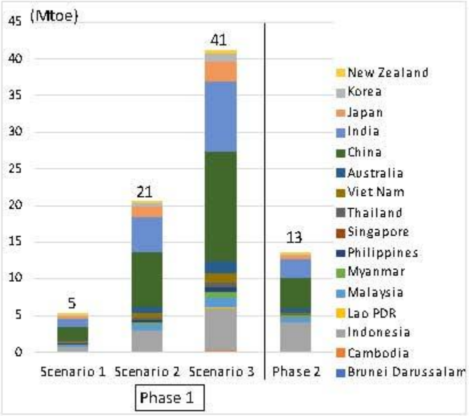


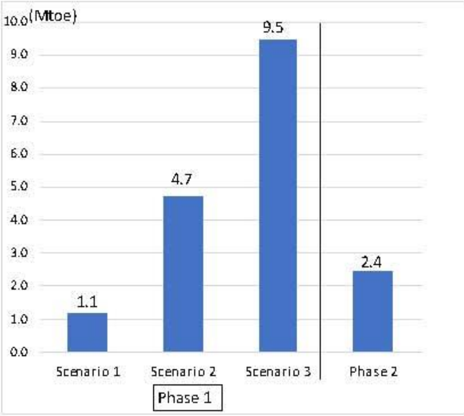


China will have the largest Potential in EAS region.
Compared to the Phase 1 Study, the Potential of India will decrease in the Phase 2 Study because Coal was excluded.

Hydrogen Demand Potential

Sector: Transport





Note; Some corrections are included from the ERIA Phase 2 Report.

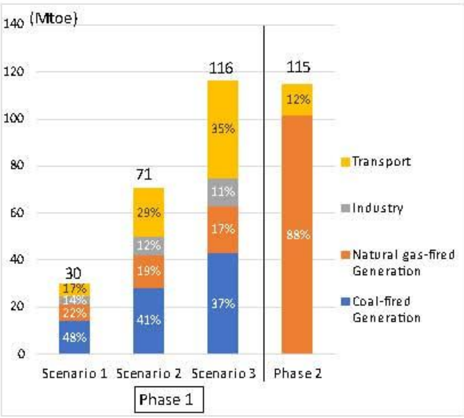
China and Indonesia will have the largest Potential in EAS region. India has the third largest Potential.

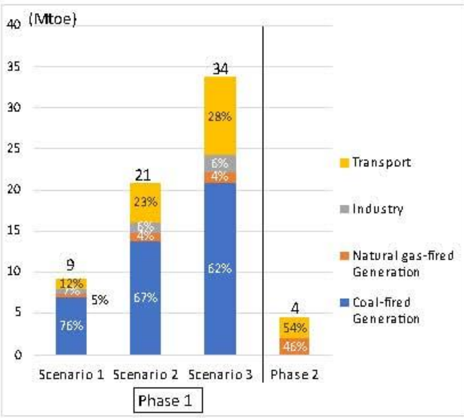
Compared to the Phase 1 Study, the Potential of India will decrease in the Phase 2 Study because Diesel is excluded.

6

Hydrogen Demand Potential

Sector: Total





Note; Some corrections are included from the ERIA Phase 2 Report.

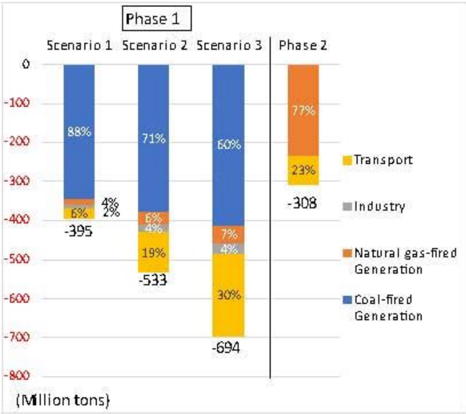
In the Phase 2 Study, Industry sector was excluded.

7

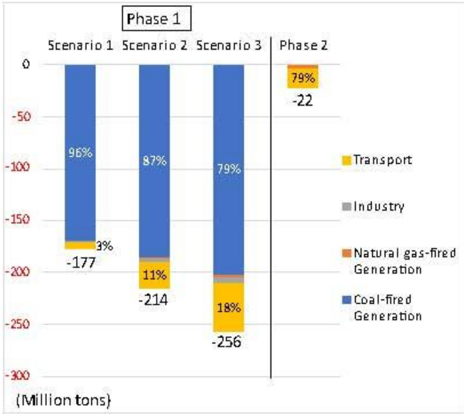
CO_2 Emission Reduction

Sector: Total

EAS



India



Note; Some corrections are included from the ERIA Phase 2 Report.

Compared to the Phase 1 Study, CO_2 Emission Reduction will be decrease because Coal was excluded in the Phase 2 Study.

Appendix

Scenario (Phase 1)

Sector	Fuel		Scenario 1	Scenario 2	Scenario 3
			H2 concenteration of mixed fuel		
Electricity generation	Coal	20% of new Coal-fired electricity generation (TWh) will be converted to Natural gas and H2 mixed fuel-fired generation	H2: 10% Nat gas: 90%	H2: 20% Nat gas: 80%	H2: 30% Nat gas: 70%
	Natural gas	20% of new Natural Gas-fired electricity generation (TWh) will be converted to Natural gas and H2 mixed fuel-fired generation			
Indistry	Natural gas	20% of Natural gas consumption for Industrial purpose will be replaced by Natural gas andH2 mixed fuel.			
			Share of H2/ Gasoline		
Transport	Gasoline	Passenger Fuel Cell Vehicle: Gasoline demand will be converted to H2	OECD H2: 2.0% Gasoline: 98% Non-OECD H2: 1.0% Gasoline: 99%	OECD H2: 10% Gasoline: 90% Non-OECD H2: 5% Gasoline: 95%	OECD H2: 20% Gasoline: 80% Non-OECD H2: 10% Gasoline: 90%
			Sahre of H2/ Diesel for Transport (Total)		
	Diesel	Fuel Cell Bus: Diesel demand will be converted toH2	Japan H2: 0.05% Diesel: 99.95% Other countries H2: 0.025% Diesel: 99.975%	Japan H2: 0.1% Diesel: 99.9% Other countries H2: 0.05% Diesel: 99.95%	Japan H2: 0.2% Diesel: 99.8% Other countries H2: 0.1% Diesel: 99.9%
			Sahre of H2/ Diesel for Transport (Rail Transport)		
	Diesel	Fuel Cell Train: Diesel consumption for Rail Transport will be converted to H2	H2: 5% Diesel: 95%	H2: 10% Diesel: 90%	H2: 20% Diesel: 80%

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Classification of Countries (Phase 2)

Future hydrogen demand in a country is likely to be greatly affected by the balance between the hydrogen supply cost and the income level of a country.

		Hydrogen Supply Cost: Cheap	Hydrogen Supply Cost: Expensive
Income Level	High	**A** The hydrogen supply costs are low, and the income levels are high. **The most widespread use of hydrogen can be expected.** Australia Brunei Darussalam Indonesia Malaysia (Sabah and Sarawak) New Zealand	**B** The hydrogen supply costs are high, and the income levels are high as well. **The use of hydrogen can be expected through a hydrogen promotion policy.** China Japan Korea Malaysia (Peninsula) Singapore Thailand
	Low	**C** The hydrogen supply costs are low, and the income levels are low as well. **The use of hydrogen is limited. Becomes a hydrogen exporter.** India Lao PDR Myanmar	**D** The hydrogen supply cost is high, and the income level is low. Hydrogen demand is unlikely to be expected. Cambodia Philippines Viet Nam

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Scenario (Phase 2)

Quadrant A

Sector	Assumption	Conversion Ratio
Electricity generation	Full-scale hydrogen use will begin in 2030 (Assume that 10 years will be required to build a large-scale hydrogen production plant, domestic supply infrastructure, and hydrogen-fired CCGT.) Hydrogen will be supplied to the power plant through newly constructed hydrogen pipelines.	The ratio of conversion to hydrogen and natural gas mixed fuel or pure hydrogen. 50%
	Existing natural gas power generation (TWh) as of 2030 will be partially converted to the 30% hydrogen and 70% natural gas mixed fuel by replacing the combustors.	
	New natural gas power generation (TWh) after 2030 will be partially converted to the 100% hydrogen fuel.	
Transport	Assume a certain share of the zero-emission vehicle (ZEV) in the registered passenger cars in 2040. Fuel cell vehicle (FCV) share in ZEV: 20%	The ratio of ZEV 50%

Scenario (Phase 2)

Quadrant B-1

Sector	Assumption	Conversion Ratio
Electricity generation (Existing generation)	Full-scale hydrogen use will begin in 2030 (Assume that 10 years will be required to build a large-scale hydrogen production plant, domestic supply infrastructure, and hydrogen-fired CCGT.) Japan, the Republic of Korea, Malaysia (Peninsula), Singapore, and Thailand are assumed to construct hydrogen import terminals adjacent to liquefied natural gas (LNG) import terminals for power generation. Other than Singapore, existing gas pipelines will be used to distribute hydrogen in a country. If gas power plants are connected to the same gas pipeline network, they will be converted to hydrogen at once.	The ratio of conversion to hydrogen and natural gas mixed fuel or pure hydrogen
	Existing natural gas-fired electricity generation (TWh) as of 2030 will be partially converted to the 30% hydrogen and 70% natural gas mixed fuel by replacing the combustors.	
	Malaysia (Peninsula) Imported hydrogen.	50%
	Thailand Gas power plants connected to LNG import terminals will be converted. The gas power plants in the following two areas are not subject to conversion: The south eastern area that receives natural gas from the JDA with Malaysia, – The north-western area that natural gas is imported from Myanmar.	50%
	China China will have a mix of domestic fossil–fuel reformed hydrogen and imported hydrogen.	50%
	Japan Imported hydrogen	50%
	Korea The KOGAS high-pressure gas pipeline connected to the gas-fired plants is looped.	100%
	Singapore The country is small. It is assumed that new hydrogen pipeline will be constructed. The number of gas-fired plants may be very small.	100%

Scenario (Phase 2)

Quadrant B-2

Sector	Assumption	Conversion Ratio
Electricity generation (New generation)	**New** natural gas power generation (TWh) after 2030 will be partially converted to the 100% hydrogen fuel. Japan,Korea Singapore, and Thailand are assumed to construct new 100% hydrogen thermal power adjacent to the hydrogen import terminals, which will not be connected to the existing natural gas pipelines. China will have a mix of domestic fossil fuel–reformed hydrogen and imported hydrogen.	
	Malaysia (Peninsula) **Thailand** **China** **Japan** **Republic of Korea**	50%
	Singapore The number of gas-fired plants may be very small.	100%
Transport	Assume a certain share of the zero-emission vehicle (ZEV) in the registered passenger cars in 2040. FCV share in ZEV: 10%	The ratio of ZEV 30%

Scenario (Phase 2)

Quadrant C

Sector	Assumption	Conversion Ratio
Electricity generation	Full-scale hydrogen use will begin in 2040 (assume it will take 20 years to improve income levels) Hydrogen is supplied to the power plant through newly constructed hydrogen pipelines.	The ratio of conversion to mixed fuel
	Existing natural gas–fired electricity generation (TWh) as of 2030 will be partially converted to the 30% hydrogen and 70% natural gas–mixed fuel by replacing the combustors except for the Lao PDR that has no plan of introducing natural gas–fired plant.	30%
	A new 100% hydrogen-fired plant will be operated in 2040 except for the Lao PDR. The generation capacity is assumed to be 200 MW.	One 200 MW plant
Transport	Assume a certain share of the zero-emission vehicle (ZEV) in the registered passenger cars in 2040. FCV share in ZEV: 10%	The ratio of ZEV 30%

Scenario (Phase 2)

Quadrant D

Sector	Assumption	Conversion Ratio
Electricity generation	Full-scale hydrogen use will begin in 2040 (Assume it will take 20 years to improve income levels). As of 2040, a pilot project or first plant will be introduced. Assume that a hydrogen import terminal will be constructed adjacent to the liquefied natural gas (LNG) terminal that is expected to be developed in the future. Cambodia will also consider importing hydrogen from the Lao PDR through pipelines.	
(Existing generation)	Existing natural gas power generation (TWh) as of 2030 will be partially converted to the 30% hydrogen and 70% natural gas mixed fuel by replacing the combustors.	
	Viet Nam	30%
	Cambodia **Philippines** The number of gas-fired plants may be very small.	100%
(New generation)	No new 100% hydrogen-fired plant will be operated in 2040.	-
Transport	Assume a certain share of the zero-emission vehicle (ZEV) in the registered passenger cars in 2040. FCV share in ZEV: 5%	The ratio of ZEV 30%

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Calculation of Hydrogen Demand Potential (Electricity generation sector)

Baseline: Electricity Generation Outlook

TWh

Country	EAS			India		
Fuel	2015	2030	2040	2015	2030	2040
Coal	6,210	8,791	10,745	1,042	2,389	3,599
Oil	184	104	83	23	14	0
Natural gas	*1,173*	*2,083*	*3,003*	*68*	*154*	*230*
Nuclear	382	1,193	1,352	37	133	186
Hydro	1,510	1,945	2,126	138	253	320
Geothermal	31.7	46.8	64.4	0.0	0.0	0.0
Others	500	1,765	2,494	75	313	473
Total	9,883	15,928	19,868	1,383	3,255	4,809

Source: ERIA Energy Outlook 2019

Assumption of Thermal Efficiency and Hydrogen Specification

Thermal efficiency*1	Coal: 55% Natural gas: 63% Hydrogen: 63%
Hydrogen specification*2	Gas density: 0.0835 kg/m^3 Net calorific value: 10,780 kJ/m^3 = 2,575 kcal/m^3 = 30,834 kcal/kg = 3,884 m^3/toe

Source: *1 High Efficiency of Thermal Power, November 2017, Agency for Natural Resources and Energy, Ministry of Energy, Trade, and Industry (Japanese only).
*2 Iwatani Corporation.

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Calculation of Hydrogen Demand Potential (Transport sector)

In order to calculate the hydrogen demand potential, it must be assumed the differential of mileage between conventional internal combustion engine car and FCV although very limited information. We select TOYOTA CROWN as internal combustion engine car and TOYOTA MIRAI as FCV because dimensions are similar.

We assume that the fuel mileage of FCV is **1.8** times better than internal combustion engine car.

Comparison between TOYOTA CROWN and TOYOTA MIRAI

	CROWN	MIRAI
Appearance		
Dimensions (cm) Length Width Height	4,910 1,800 1,455	4,890 1,815 1,535
Weight (kg)	1,590–1,650	1,850
Displacement	2,000 cc	-
Fuel mileage (JC08 mode)	12.8 km/ litre (16,372 km/ toe)	7.59 km/ m3 (29,480 km/ toe)
	MIRAI's fuel mileage is 1.8 times better	

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Thank you for your attention!

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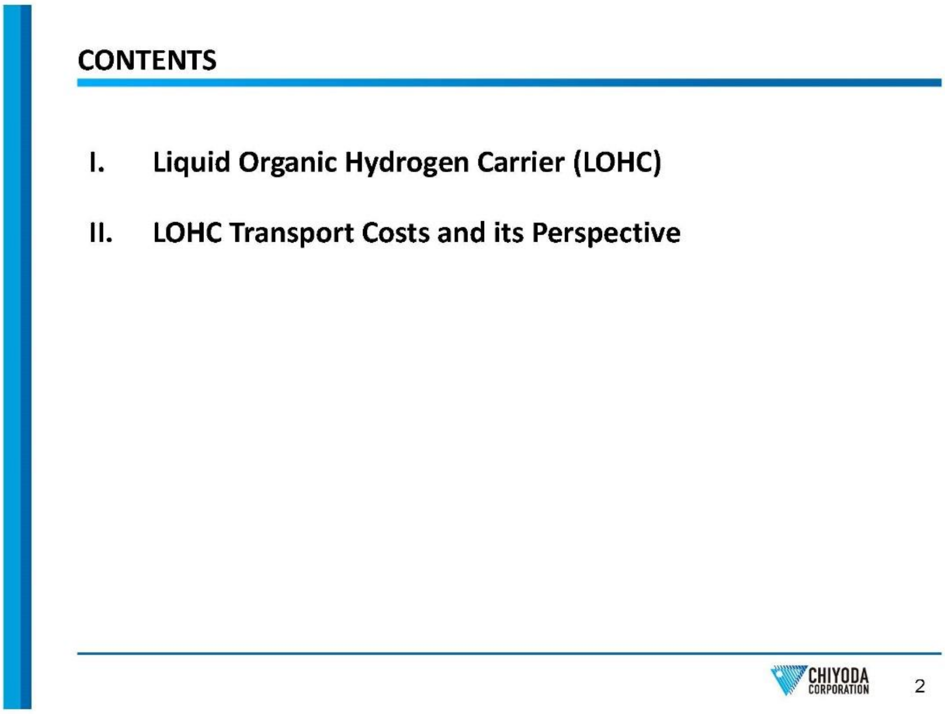
4. Session 4: Introduction of Hydrogen Transport Costs (Liquefied Hydrogen) by Chiyoda Corporation



I. Liquid Organic Hydrogen Carrier (LOHC)

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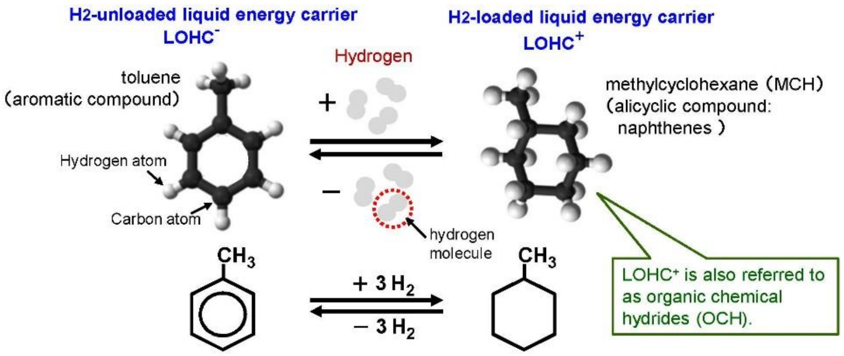
Liquid Organic Hydrogen Carrier (LOHC)

- The hydrogen energy storage solution is based on two separate processes, namely the loading (hydrogenation) and unloading (dehydrogenation) of a liquid energy carrier.
- An important advantage of the hydrogen being chemically bonded to the liquid carrier is that it can be stored under ambient temperature and pressure without suffering any self-discharge or the loss of hydrogen.



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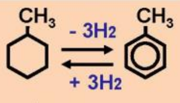
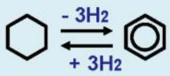
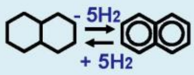
Liquid Organic Hydrogen Carrier (LOHC) : Several types

	MCH－Toluene		Cyclohexane －Benzene		Decaline－Naphthalene	
	MCH	**Toluene**	Cyclohexane	Benzene	Decaline	Naphthalene
Molecular formula	C_7H_{14}	C_7H_8	C_6H_{12}	C_6H_6	$C_{10}H_{18}$	$C_{10}H_8$
Chemical equation	 ⊿H = 205 kJ/mol		 ⊿H = 206 kJ/mol		 ⊿H = 332 kJ/mol	
Molar mass(g/mol)	98.2	92.1	84.2	78.1	138.3	128.2
Phase @RT	**Liquid**	**Liquid**	**Liquid**	**Liquid**	**Liquid**	**Solid**
Density(g/cm^3)	0.77	0.87	0.78	0.87	0.90	0.98
Melting point (deg.C)	**-127**	**-95**	**7**	**6**	Cis:**-43** Trans:**-30**	**80**
Boiling point (deg.C)	101	111	81	80	Cis:195 Trans:186	218
H_2 store density (wt%)	6.2	—	7.2	—	7.3	—
H_2 store density ($kg\text{-}H_2/m^3$)	47	—	56	—	65	—

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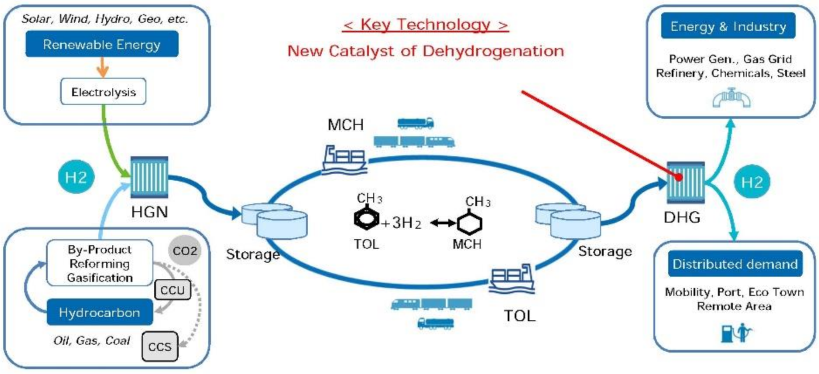
MCH Hydrogen Supply Chain Overview

- Chiyoda has established a large and efficient H_2 storage and transportation system.
- Methylcyclohexane (MCH), an H_2 carrier, remains a liquid under normal temperature and pressure.



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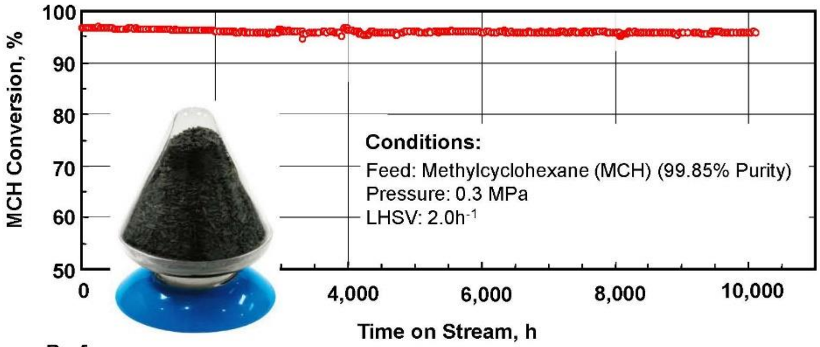
Key Features of MCH Hydrogen Technology

Long term storage & long distance transportation	Chemically stable, minor MCH (H_2) loss during long term storage and long distance transportation
Easy to handle	Liquid under ambient temperature and pressure Approximately 1/500 in volume
Use of existing oil infrastructure	Utilize existing infrastructure, standard, regulation, to minimize social investment for H2 introduction
Storage and transportation risk equivalent to petroleum products.	Safe storage and transportation that is equivalent level to petroleum products
Combination of new and proven technologies	Combination of conventional technology and new dehydrogenation catalyst technology

MCH Technology Development : Phase 1 (Laboratory)

- Chiyoda succeeded in developing a dehydrogenation catalyst at its R&D center in 2008 that has achieved optimum performance over 12,000 hrs continuous operation.

Dehydrogenation Catalyst Development in Yokohama



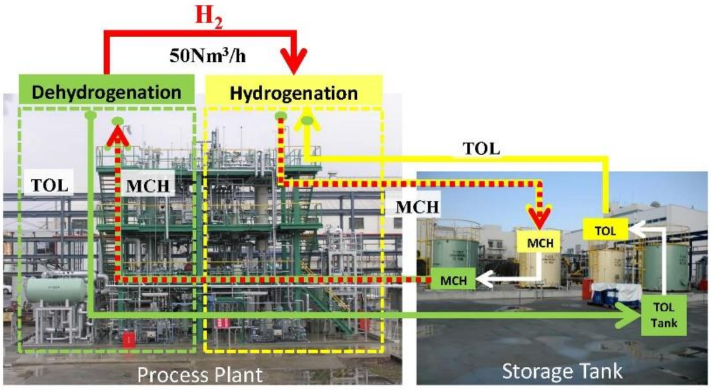
Performance

- **MCH conversion: >95%, Toluene selectivity; >99.9%, H_2 yield: >95%**
- **H_2 generation rate: >1,000 Nm^3-H_2/h/m^3-cat. (1,000 Ncm^3-H_2/h/cm^3-cat.)**
- **Catalyst life: >10,000hr**

MCH Technology Development : Phase 2 (Pilot Test)

- Chiyoda confirmed the performance and long life of the catalyst through 10,000 hours continuous operation of its pilot plant from April 2013 to November 2014

SPERA Hydrogen Demonstration Plant in Yokohama



MCH Technology Development : Phase 3 (Demonstration)

- Chiyoda and partners established the Advanced Hydrogen Energy chain Association for technology Development ("AHEAD") and initiated the world's first global hydrogen supply chain demonstration project

Description	
Scale	210 tons/year (maximum)
Duration	March 2020 - December 2020
Hydrogen Supply	Brunei Darussalam (Hydrogen Production)
Hydrogen Demand	Kawasaki City (fuel for gas turbine power plant)
Transportation	ISO tank container (container ship/truck)
Business Scheme	Establishment of the Association for Technology Development. NEDO Funded Project*

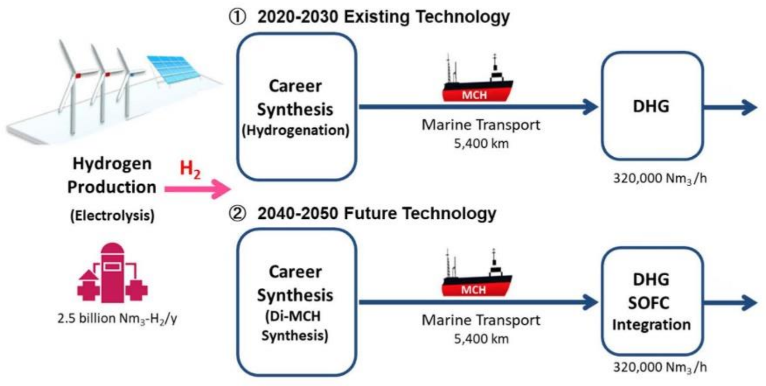
* Technology Development for the Realization of a Hydrogen Society (funded by NEDO)
"Demonstration of the Hydrogen Supply Chain by the Organic Chemical Hydride Method Utilizing Unused Energy"

II. LOHC Transport Costs and its Perspective

Model of Global Hydrogen Supply Chain

- Two global hydrogen supply chain models are proposed to compare the hydrogen costs: 2020–2030 Existing Technology model (Existing model) utilizing existing technologies, and 2040–2050 Future Technology model (Future model) utilizing future advanced technologies

Model for Global Hydrogen Supply Chain



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Model of Global Hydrogen Supply Chain : Future Technology

- The advanced technologies employed for the Future model are listed as follows.

Future technologies:

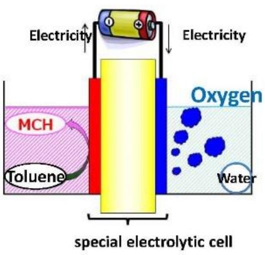
- ✓ Process simplification, such as MCH direct synthesis (Tokyo University, 2019), employed as a substitute for the combination of electrolysis and hydrogenation (HGN)
- ✓ Transportation efficiency Improvement utilizing Super Eco Ship (NYK)
- ✓ Energy efficiency improvement of dehydrogenation by catalyst performance increase
- ✓ Heat integration optimization using SOFC exhaust gas to dehydrogenation heat

Model of Global Hydrogen Supply Chain : Future Technology (1)

- MCH is produced directly from electricity, water and toluene through an integrated process of electrolysis and hydrogenation (MCH electrochemical synthesis technology).

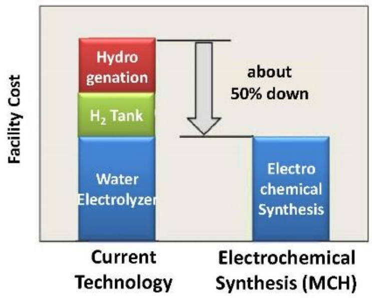
MCH Electrochemical Synthesis Technology

(Electricity -> MCH)



* *Laboratory scale test completed in 2019*

Facility Cost Reduction Potential



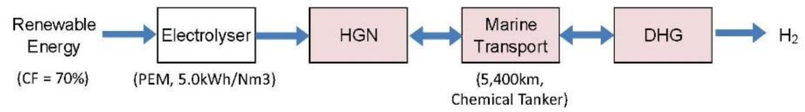
* *In case of 6,000 Nm^3/h-H_2 (3 MW scale)*

(Source) Press Release from JXTG / Chiyoda / University of Tokyo / QUT

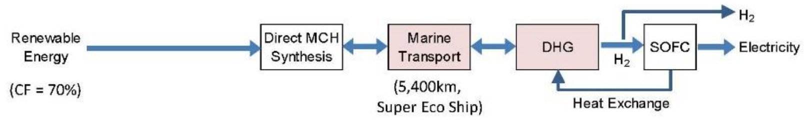
Model of Global Hydrogen Supply Chain : Key Assumptions

- In the 2020–2030, hydrogen is produced by PEM electrolysis, chemically fixed to toluene (hydrogenation), transported by chemical tankers and extracted by dehydrogenation.
- In the 2040–2050, renewable power will directly synthesize MCH, transported by Super Eco Ships, and hydrogen will be extracted in the dehydrogenation with SOFC exhaust heat.

1. 2020 – 2030 Existing Technology



2. 2040 – 2050 Future Technology



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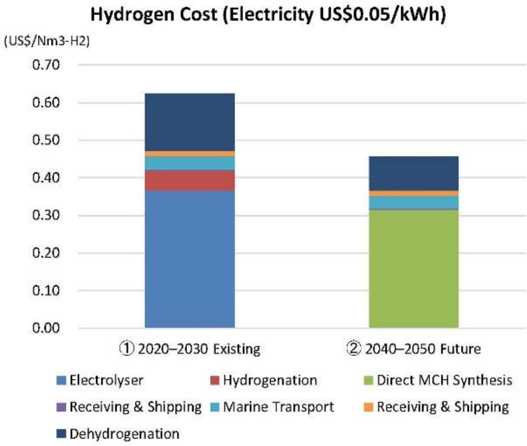
Global Hydrogen Supply Chain Cost (US$0.05/kWh)

- At the electricity price of US$0.05/kWh, the hydrogen price in 2040–2050 is estimated to be reduced by around 25%, compared to US$0.62/Nm3 in 2020–2030.



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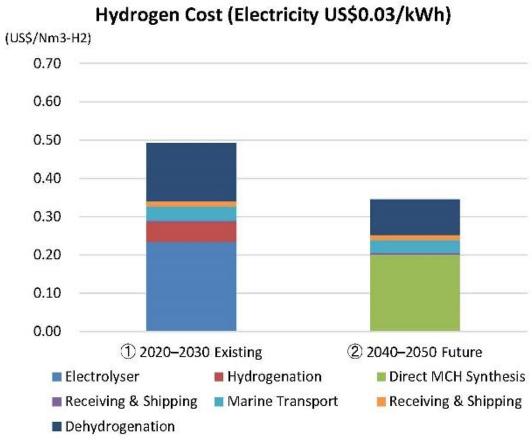
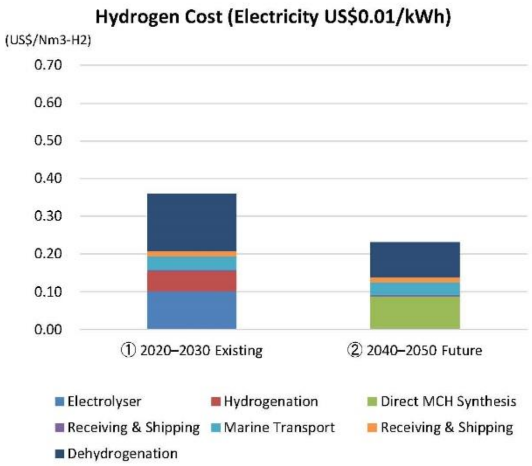
Global Hydrogen Supply Chain Cost (US$0.03/kWh)

- At the electricity price of US$0.03/kWh, the hydrogen price in 2040–2050 is estimated to be reduced by around 30%, compared to US$0.49/Nm3 in 2020–2030.



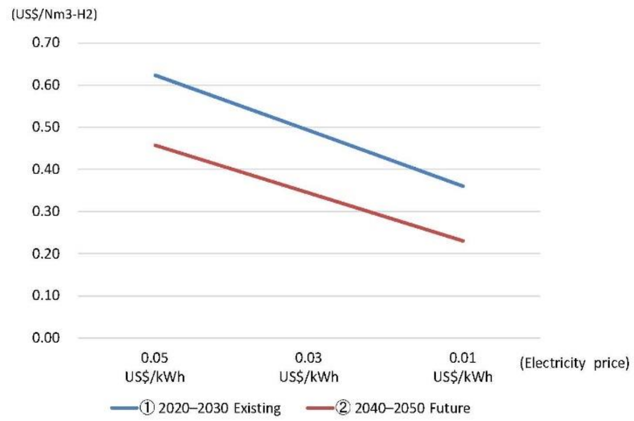
Global Hydrogen Supply Chain Cost (US$0.01/kWh)

- At the electricity price of US$0.01/kWh, the hydrogen price in 2040–2050 could be reduced to around US$0.23/Nm3, nearly 35% reduction, compared to existing model in 2020–2030.



Global Hydrogen Supply Chain Cost : Summary

- The study showed that the total hydrogen supply chain cost could be reduced by around 20%–30% broadly owing to future technology improvements, like MCH direct synthesis, catalyst performance upgrades, and heat integration of SOFC exhaust gas to dehydrogenation.



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Thank You

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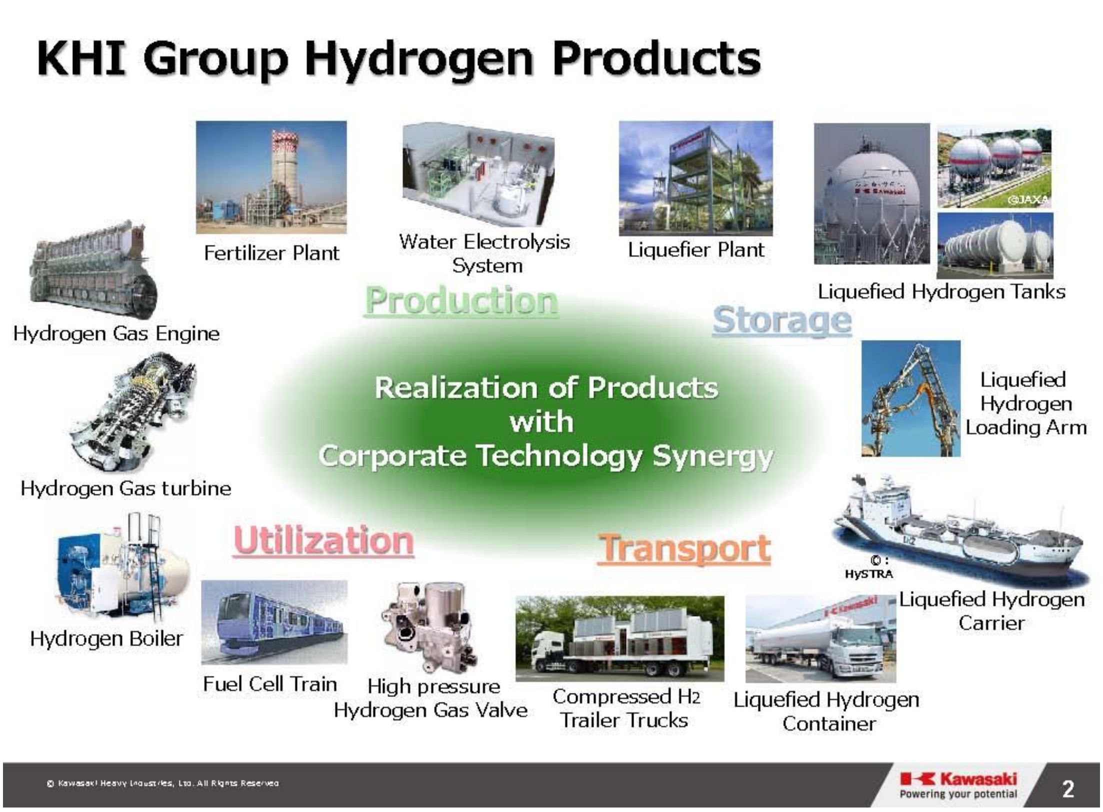
5. **Session 5: Introduction of Hydrogen Transport Costs (Liquefied Hydrogen) by Kawasaki Heavy Industries**



Toward large volume hydrogen utilization essential for decarbonization

Energy system only with renewables and battery storage has a limit for energy scale, facility cost and applications.

Liquefied hydrogen enables large amount, long-distance, long-term transportation and storage of energy and connects multiple sectors.

With extremely wide range of industries involved in hydrogen supply chain and demand field, hydrogen is highlighted worldwide due to creating a virtuous cycle for environment and economy.

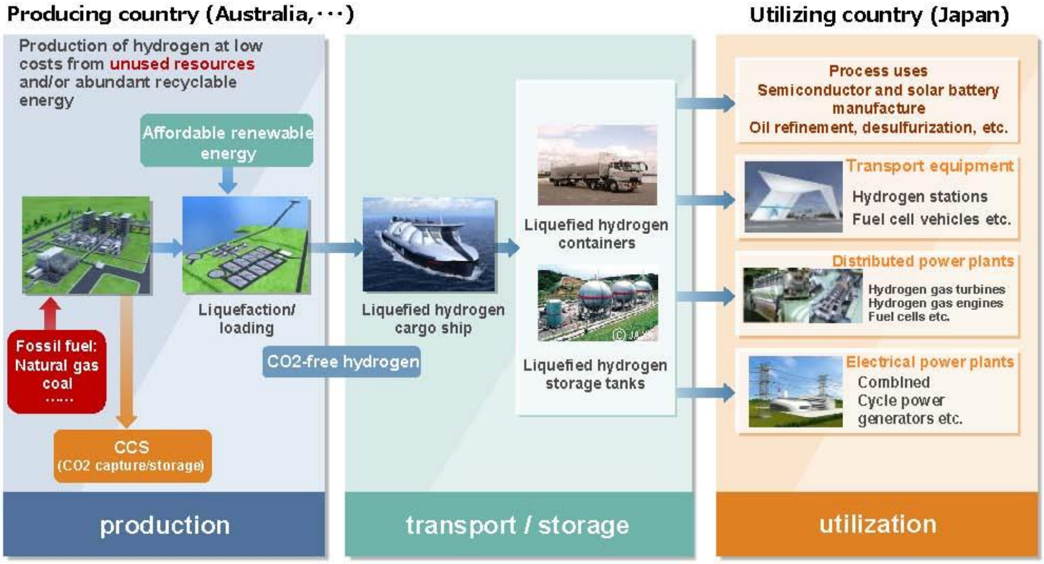
Kawasaki Heavy Industries contributes to achievement of decarbonization as the sole company in the world that owns the whole hydrogen supply chain technology for production, transportation, storage and utilization.

CO_2-Free Hydrogen Resources in the World

- Hydrogen can be produced from various sources and procured from many countries → Contribute to energy security
- Large amount, long-distance, long-term transportation and storage of energy and sector integration are possible with hydrogen → Contribute to resilience

Concept of CO_2-free Hydrogen Chains

Stable energy supply while suppressing CO2 emissions



Liquefied Hydrogen
~ Large-scale Transport Methods for Hydrogen ~

- Extremely low temperature (-253 degrees C)
- 1/800 the volume of hydrogen gas
- Transport medium of proven practical use in industry and as rocket fuel
- Non-toxic, odorless and no greenhouse effect
- High purity = no need for refinement (can be supplied to fuel cells by evaporation alone)

Purity of liquefied hydrogen is enough high (99.999% or more) to meet the requirement for FCV fuel (99.97% or more)

*ISO14687-2 Hydrogen fuel product specification

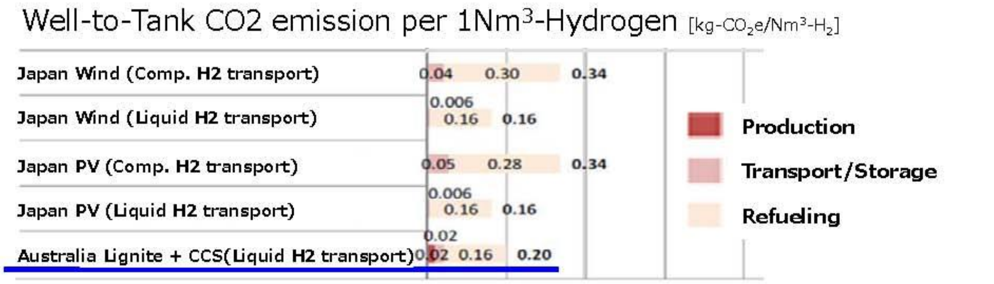
Liquefied hydrogen tanks (Tanegashima Rocket Base)

Largest liquefied hydrogen tanks in Japan (Kobe)

Commercial LH2 Carrier (Future)

LCA by Mizuho Information & Research Institute

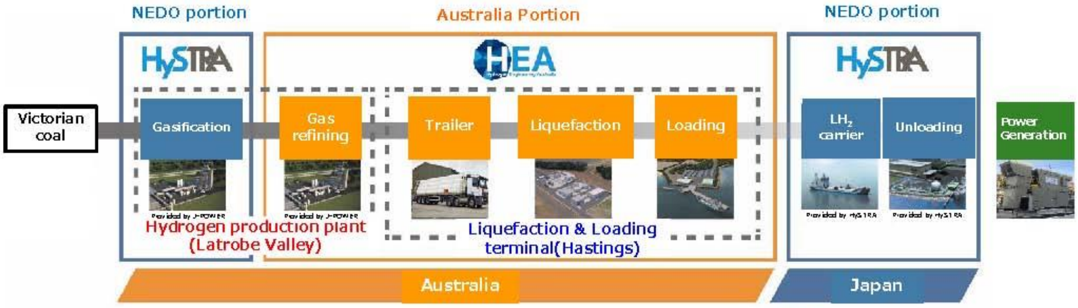
- Low CO2 emission equivalent to renewable oriented hydrogen



LCA by Mizuho Information & Research Institute
Ref: https://www.mizuho-ir.co.jp/publication/report/2016/pdf/wttghg1612.pdf

HESC Pilot Project Structure

Kawasaki is working with a number of partners on HESC Pilot Project supported by the governments of Japan and Australia.



CO2-free Hydrogen Energy Supply Chain Technology Research Association (HySTRA)

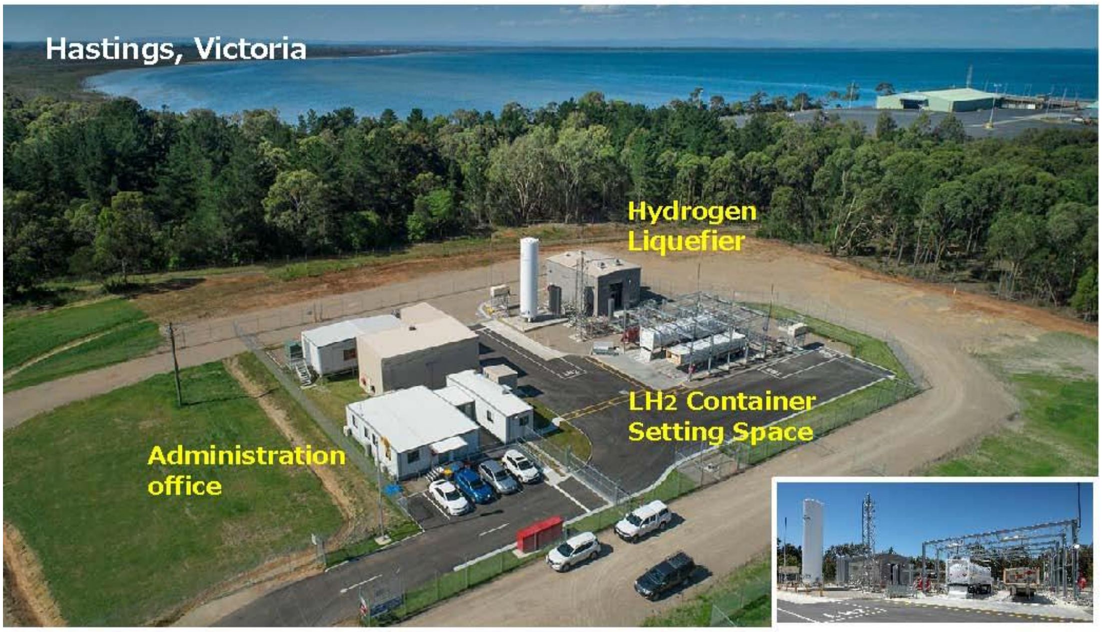
Kawasaki, Iwatani, J-Power, Shell Japan
Marubeni, ENEOS, KLINE
Supported by NEDO and METI

Hydrogen Engineering Australia (HEA)

Kawasaki, J-Power, J-Power Group, Iwatani
Marubeni, Sumitomo, AGL
Supported by Victorian and Australian Governments

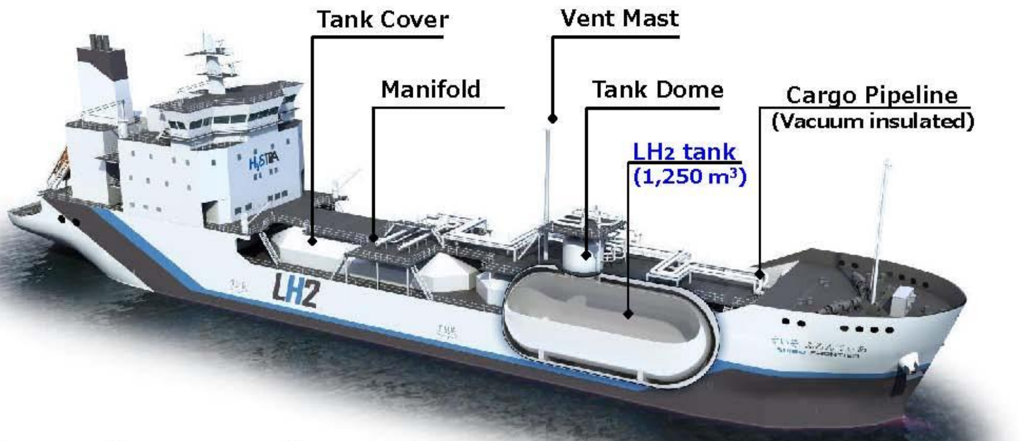
*NEDO : New Energy and Industrial Technology Development Organization
*METI: Ministry of Economy, Trade and Industry

Hydrogen Liquefier and Loading Base



Liquefied Hydrogen Carrier "Suiso Frontier"

Suiso: Hydrogen in Japanese



Length	116 m	Speed	13 knot
Width	19 m	Draft	4.5 m
Max crew	25 person	Propulsion	Diesel electric

© HySTRA

LH_2: Liquefied Hydrogen

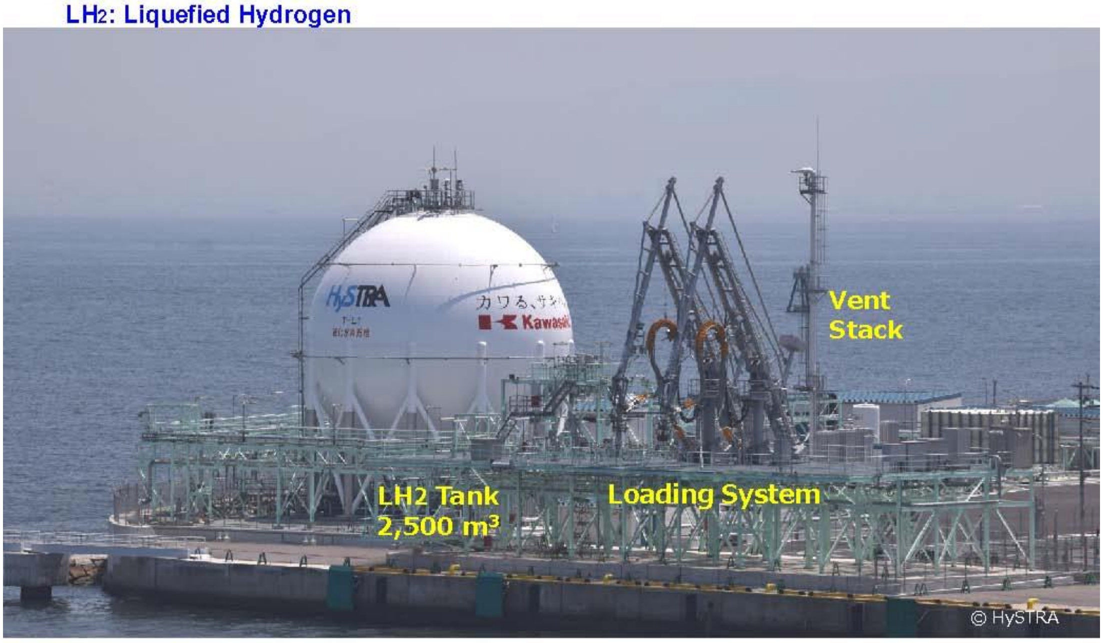
Liquefied Hydrogen Carrier "Suiso Frontier"

Launch ceremony
at KHI Kobe Factory
(11 December 2019)

Cargo Tank Installation
at KHI Harima Works
(7 March 2020)

LH2 Receiving Terminal

LH2: Liquefied Hydrogen



Development of Scaling Up on LH_2

LH_2: Liquefied Hydrogen

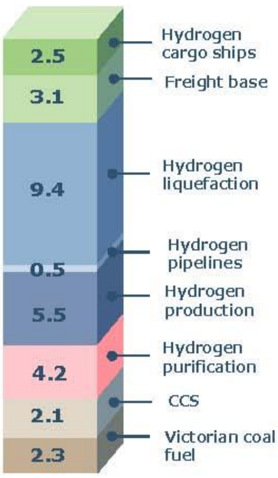
Pilot ship tank: 1,250m^3 — **Commercial ship tank: 40,000m^3**

Pilot terminal tank: 2,500m^3 — **Commercial terminal tank: 50,000m^3**

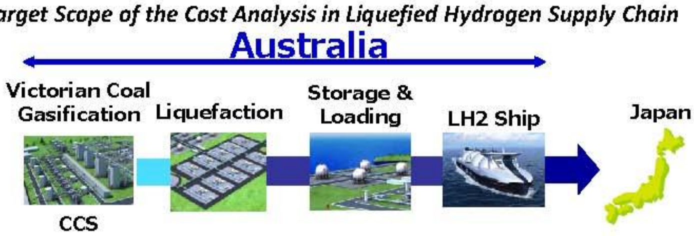
Interface equipment (ex: Loading arm) **also under development**

Estimation of hydrogen cost in 2030

Hydrogen cost (CIF)@2030
29.7 yen/Nm^3



Target Scope of the Cost Analysis in Liquefied Hydrogen Supply Chain

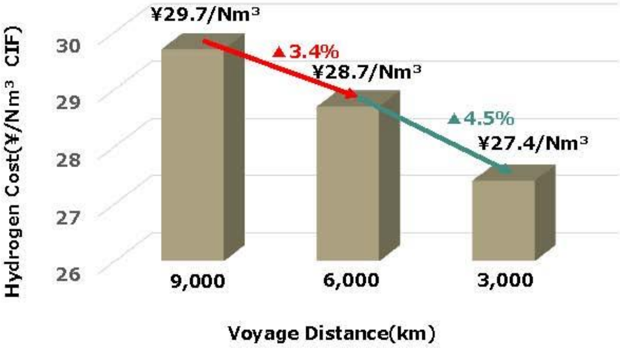


Precondition for Hydrogen Cost Calculation in 2030

Item	Unit	FS results
Victorian Coal Consumption	Mt / y	4.74
Victorian Coal Cost	AU$ / t	15
CCS Amount	Mt / y	4.39
CCS Cost	AU$ / t	15
Hydrogen Production	t / d	770
Hydrogen import in JPN	t / y	225,540

Item	Unit	Condition
Project period	year	30
Borrowing period	year	15
Years of depreciation	year	15
Tax	%	30
Investment and debt ratio	-	50 : 50
Borrowing rate	%/y	3

Analysis on Hydrogen Transport Costs by Voyage Distance



Voyage Distance(km)	9000km	6000km	3000km
Hydrogen Cost(¥/Nm3 CIF)	29.7	28.7	27.4

Possibility of Hydrogen Cost Reduction in the Further Future

	2020FY	2030FY	2040FY	2050FY
	Pilot demonstration	Commercial start (2 ships operated)	40 ships operated	80 ships operated

	2020FY	2030FY	2040FY	2050FY
¥/Nm³@CIF cost Hydrogen transport amont Power generation capacity※ ※Assuming an operation rate of 90%	Technology / social demonstration	¥30/Nm³ 225 K t/y 650 MW	¥24/Nm³ 4,500 K t/y 13,000 MW	¥18/Nm³ 9,000 K t/y 26,000 MW
Power generation cost		¥16/kWh	¥14/kWh	¥11/kWh
Share of power generation CO2 reduction forecast		0.5% 3,000 K t-CO2	10% 60,000 K t-CO2	20% 120,000 K t-CO2

Role and Effect of CO_2-free Hydrogen Chain

1 Stable Supply

- Hydrogen from fossil fuel linked with CCS will realize vast and affordable energy supply

  → Contribute energy security

2 Environmental

- No CO_2 emissions when used (only water is emitted)

  → "Ultimate clean energy"

3 Improvement of Industrial Competitiveness

- Wide use of hydrogen brings Industrial growth → Deployment of Infrastructure export
- Hydrogen production started from fossil fuel shifted to the renewables in the future → Sustainability

Thank you for listening

Kawasaki, working as one for the good of the planet

世界の人々の豊かな生活と地球環境の未来に貢献する

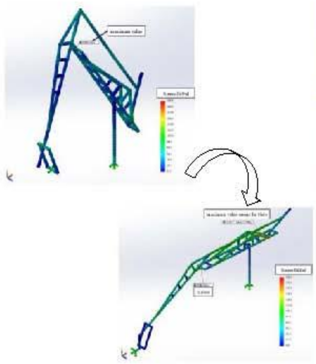
“Global Kawasaki”

Kawasaki Heavy Industries, Ltd.
Corporate Technology Division
https://global.kawasaki.com

Reference

Current situation -loading system-

- We applied flexible hoarse type for pilot project
- We did durability test under similar situation during operation



Simulation of maximum movable area

Subsidized by NEDO

Hydrogen Gas Turbine CGS

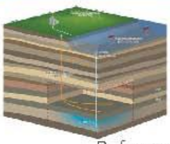
(Kobe Port Island)

Carbon Capture and Storage

- The Victorian Government and Australian Government promote CarbonNet Project
- Completed drilling an Offshore Appraisal Well (OAW) at the Pelican site in January 2020.
- Storage capacity 30Gt of CO_2 under Bass Strait

Reference : METI

CCS Image



Reference : CO2CRC HP

Reference : Carbon Net HP

Appendix 2

Workshop on the Hydrogen Potential Study of Demand and Supply Sides

ERIA-IEEJ-Malaysia Hydrogen Meeting

Virtual Workshop – 29 July 2021

The Economic Research Institute for ASEAN and East Asia (ERIA) and the Institute of Energy Economics, Japan (IEEJ) hosted a virtual workshop on 29 July 2021 on the demand and supply side of hydrogen. The objectives were to emphasise the importance of hydrogen as a source of energy, coexisting with fossil fuels, growing renewable energy, and greater sustainability. Institutions from Malaysia that attended this workshop included representatives from the Economic Planning Unit, Ministry of Environment and Water, Government of Malaysia; Energy Commission; Ministry of Energy and Natural Resources, Government of Malaysia; Ministry of Transport, Government of Malaysia; Petronas; Sustainable Energy Development Authority; and Tenaga Nasional Berhad.

ERIA prepared energy outlooks based on macroeconomic approaches. First, Malaysia's gross domestic product (GDP) growth rate from 2017 to 2050 is 3.1% per year. Second, there will be 0.9% annual population growth until 2050, from 31 million people in 2017 to 41 million in 2050. Third, Malaysia's GDP per capita is expected to rise from $11,720 in 2017 to $23,950 in 2050 (at constant 2010 prices). Finally, due to a future tight supply–demand balance, crude oil prices will rise to around $250 per barrel in 2050.

According to Malaysia's forecast, final energy consumption jumped 2.15 times between 2000 and 2017 (at a 4.6% annual rate), and the business-as-usual scenario increased 2.96 times between 2017 and 2050 (a growth rate of 3.3% per year). In addition, if Malaysia embraces the ambitious aim of improving energy efficiency, energy demand will fall by about 6% compared to business as usual. However, Malaysia is still reliant on oil and gas for final energy consumption; therefore, it remains crucial in the final energy consumption sectors and will remain so in 2050.

Malaysia's power generation sector rose 2.56 times between 2000 and 2017 (at a rate of 5.7% per year). The increase will be 2.62 times between 2017 and 2050 (3.0% per year). Malaysia will be significantly reliant on gas and coal-fired power generation in the 2050 business-as-usual scenario, but this will change as a result of policies targeted at growing hydro, geothermal, and others. Malaysia continues to rely on gas and coal-fired power generation in the business-as-usual scenario but switches to other renewable energy sources under the alternative policy scenario (APS).

Malaysia continues to rely on coal, oil, and gas for primary energy supply. Other technologies, such as solar photovoltaic (PV), are rarely used. The APS scenario for 2050 shows a 16% reduction in energy usage due to increased hydro, solar PV, and other renewables, with fossil fuels still providing the majority of the energy. Carbon dioxide (CO_2) emissions are caused by the combustion of coal, oil, or gas. As a result, CO_2 emissions increased 1.79 times (at a rate of 3.5% per year) between 2000 and 2017, and 2.74 times between 2017 and 2030 (3.1% per year). CO_2 is mostly produced by coal and oil. The utilisation of zero-carbon energy sources such as hydro, nuclear, and solar PV also rises in the APS. As a result, CO_2 emissions decrease by about 22%, although coal and oil continue to be a source of CO_2 emissions.

Many countries, particularly in Europe, North America, and Asia, have declared net-zero emission goals. ERIA has been assisting ASEAN Members in developing net-zero emission scenarios using an optimisation approach that prioritises zero-emission energy technologies such as hydrogen and carbon capture, utilisation, and storage while keeping costs to a minimum. As a result of the outlook, ERIA has begun to investigate hydrogen, which emits no CO_2, has an unlimited supply, is able to store energy beyond the seasons, and can effectively distribute natural energy and fossil fuels across the globe. Hydrogen will be a significant source of energy in the future, coexisting with present fossil fuels and developing renewable energy to ensure the planet's long-term viability. However, the challenge is how to make hydrogen economically viable, financially attractive, and socially beneficial.

The following are materials presented by ERIA, IEEJ, Chiyoda Corporation, and Kawasaki Heavy Industries.

1. Session 1: Introduction of the Hydrogen Potential Study in 2018 and 2019 by ERIA

Contents

- EAS Energy Outlook of Malaysia
  - Econometrics approach
- Net Zero Emissions
- Net Zero Emissions of Malaysia
- Why Hydrogen?
- Current Trends of Hydrogen
  - National Hydrogen Strategy by Japan
  - Hydrogen Ministerial Meeting
- Scope of Work in 2018-19 Phase 1
- Scope of work in 2019-20 Phase 2

ERIA

EAS Energy Outlook of Malaysia (Macro Assumptions)

Economic Growth

3.1 % P.A. from 2017 to 2050

Population Growth

0.9 % P.A. from 2017 to 2050

31 million persons in 2017 to increase to 41 million in 2050

GDP per capita

11,720 thousand US$/person (constant 2010 price and US$) in 2017 increases to 23,950 thousand US$/person in 2050

Crude Oil Price (nominal price)

Increase to about 250 US$/bbl in 2050 due to future tight balance between demand and supply

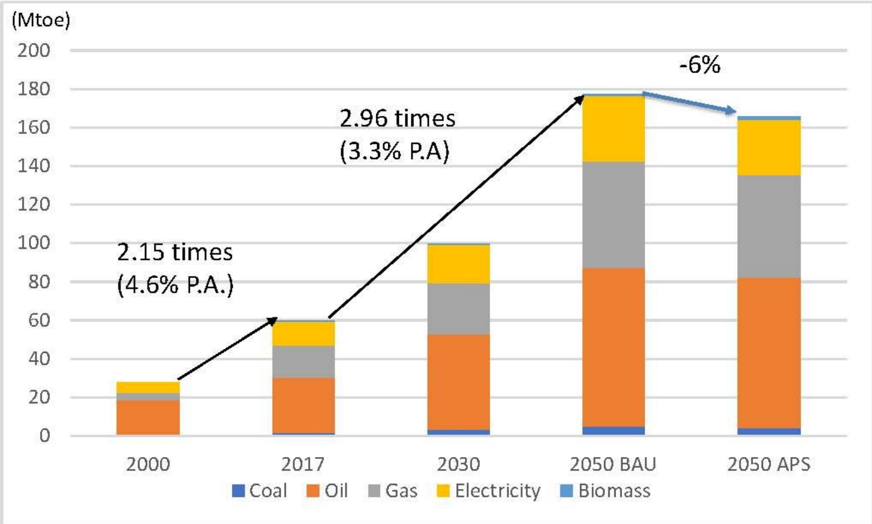
ERIA

Source: ERIA ESP WG Report 2019-20

3

EAS Energy Outlook Result of Malaysia

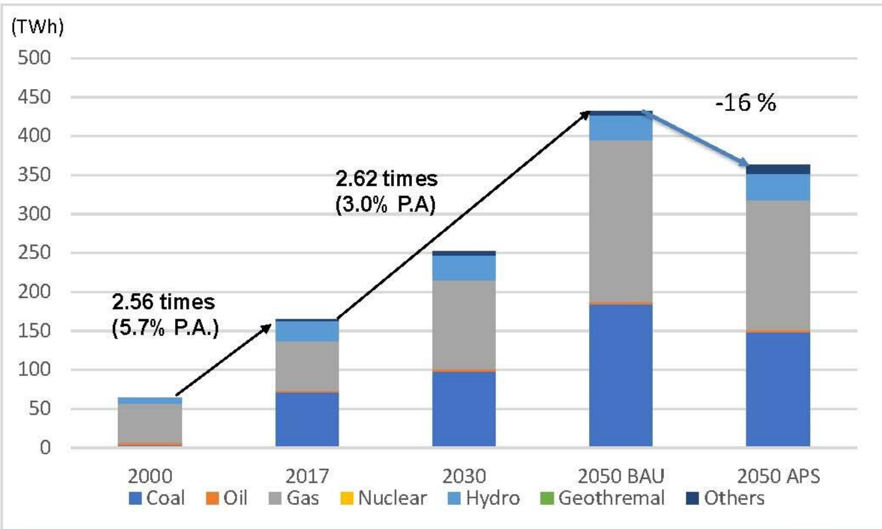
- Final Energy Consumption



Source: ERIA ESP WG Report 2019-20

EAS Energy Outlook Result of Malaysia

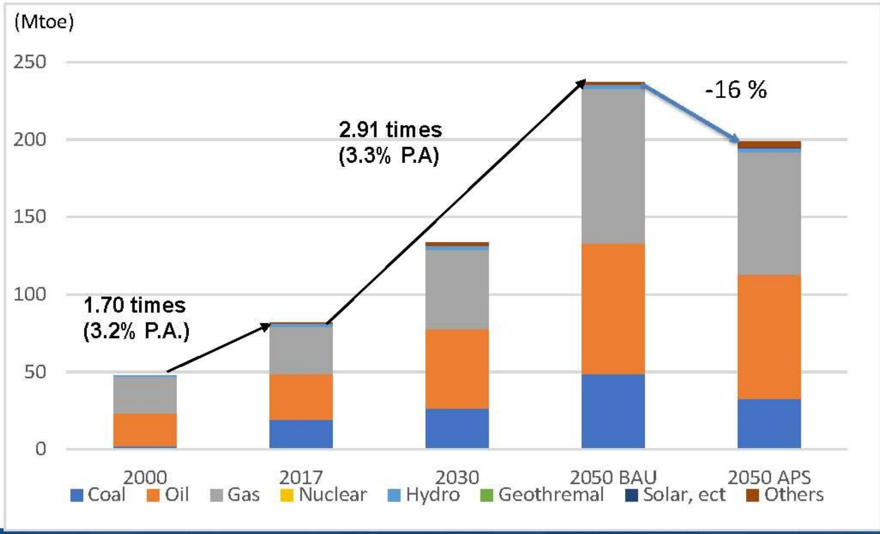
- Power Generation



Source: ERIA ESP WG Report 2019-20

EAS Energy Outlook Result of Malaysia

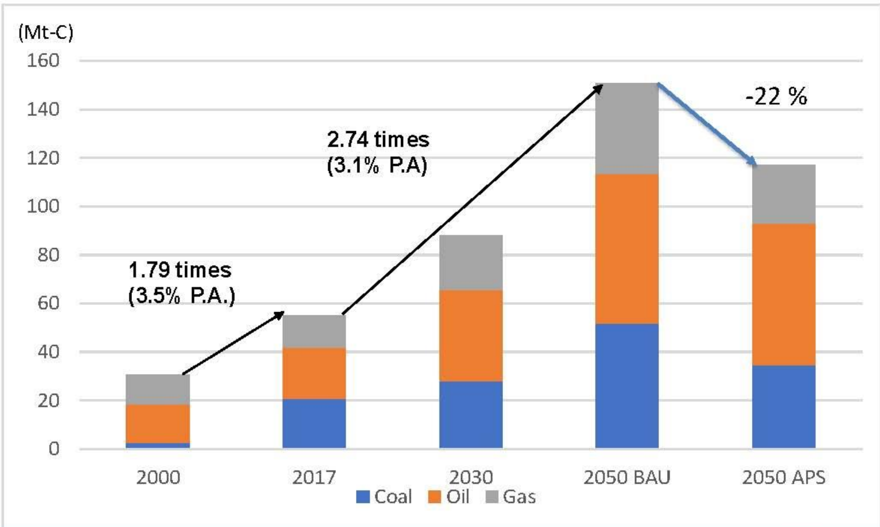
- Primary Energy Supply



Source: ERIA ESP WG Report 2019-20

EAS Energy Outlook Result of Malaysia

- CO2 Emissions

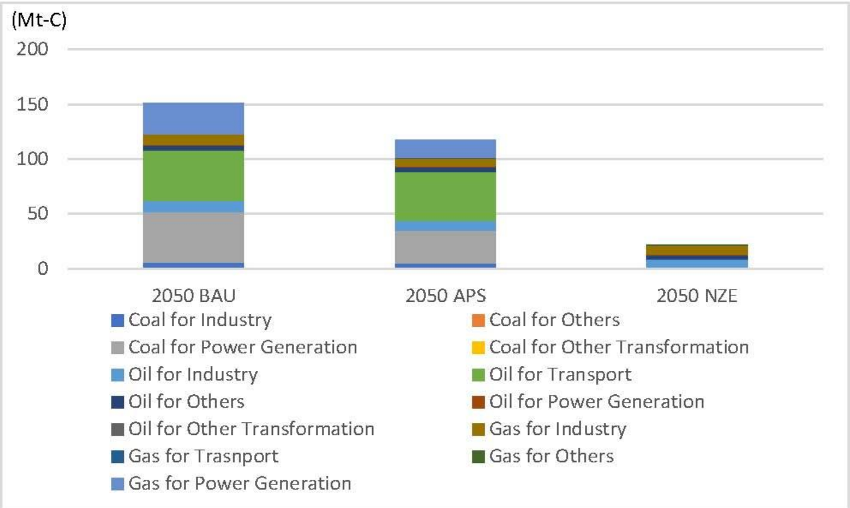


Source: ERIA ESP WG Report 2019-20

Net Zero Emissions

- Many countries especially in Europe, North America and Asia regions announce Net Zero Emissions targets;
  - European countries, Canada, US, Japan and South Korea: 2050
  - China:2060
  - Singapore: beyond 2050
- ERIA has been supporting ASEAN countries to prepare their net zero emission scenarios applying an optimization approach
  - Select zero emission energy technologies under cost minimum objective (liner programming)

Net Zero Emission of Malaysia



Hydrogen: Gas Power and Oil for transport
Ammonia: Coal for Power

WHY HYDROGEN ?

- Hydrogen will be an important source of energy, coexisting with current fossil fuels and growing renewable energy, for greater sustainability of our planet in future.
- The challenge is how to make hydrogen economically viable, financially attractive, and socially beneficial.

1. ZERO CO2 EMISSIONS

Hydrogen bonds with oxygen to generate electricity/heat, with water the only by-product.

2. UNLIMITED SUPPLY

Hydrogen can be extracted from a wide range of substances including oil, natural gas, biofuels, sewage sludge, and can be produced from unlimited natural energy by the electrolysis of water.

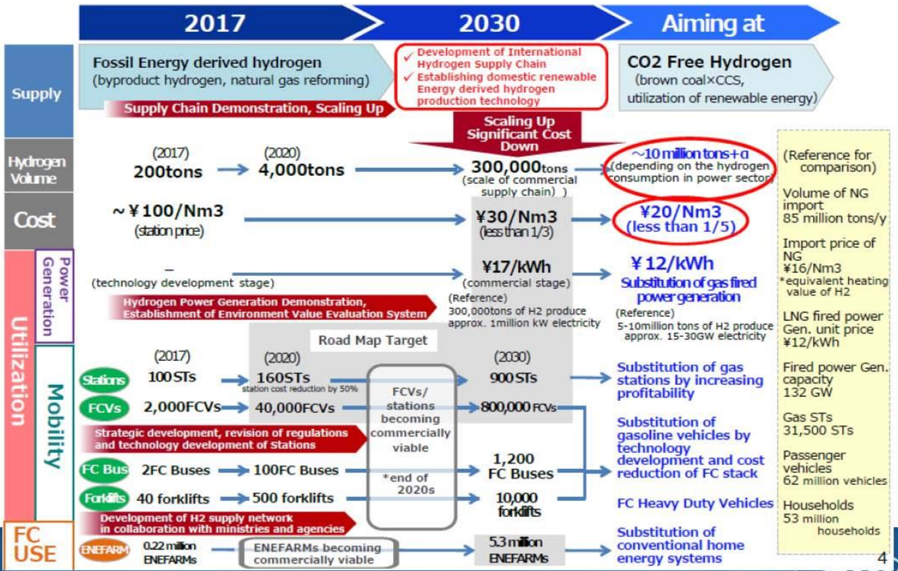
3. STORAGE AND TRANSPORTATION

Hydrogen is able to store energy beyond the seasons (from summer to winter) and transport for long distance (from south to north), to effectively utilize distributed natural energy and fossil fuels in the planet.

10

JAPAN's POLICY - Basic Hydrogen Strategy

- The Japanese Government decided on the "Basic Hydrogen Strategy (December, 2017)" to show the plan of action until 2030, the future vision in 2050.



(Source) METI "The Basic Hydrogen Strategy"

11

Current Trends of Hydrogen: 1st Hydrogen Ministerial Meeting in 2018

ERIA

Scope of Work of Hydrogen Potential Study Phase 1

- Review of renewable energy policies including hydrogen of EAS countries
- Forecasting of hydrogen demand potential of EAS countries except Russia and US
- Forecasting of hydrogen supply potential and cost
- Well to wheel analysis
- Country survey
  - Indonesia, Malaysia, Thailand
  - Australia, India, New Zealand
- Lecture workshop in Indonesia
- Studied in 2018-19

ERIA

Scope of Work of Hydrogen Potential Study Phase 2

- Review of Hydrogen Production and Supply Cost by **IEEJ**
- Review of Hydrogen Demand Potentials by **IEEJ**
    - Fuel for power generation
    - Fuel for FCV and FC train
    - Fuel for industrial use e.g. Heating boiler
- Review of hydrogen transport cost and its perspective (MCH) by **Chiyoda** Corporation
- Review of hydrogen transport cost and its perspective (LH2) by **KHI** Corporation
- EAS Hydrogen Working Group meeting
- Lecture Workshop in Thailand and Brunei Darussalam
- Studies in 2019-20

Thank you for your attention!!

2. Session 2: Hydrogen Production and Supply Cost by IEEJ

ERIA/ARCI Workshop, July 2021

Hydrogen production and supply cost

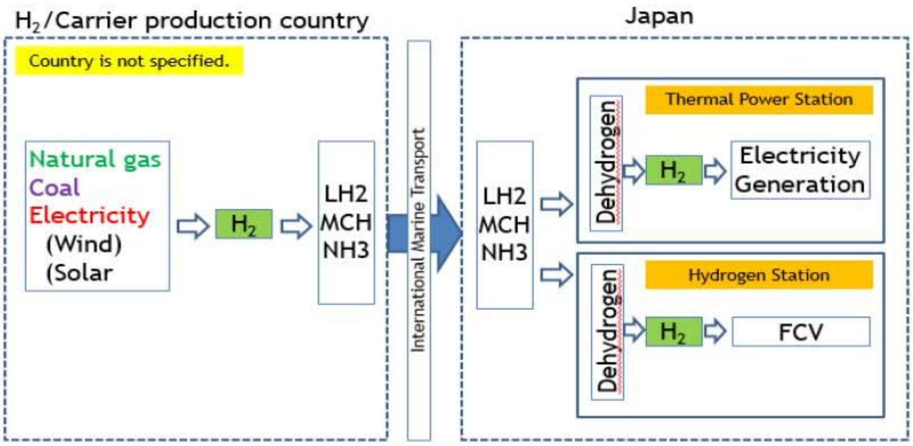
Ichiro KUTANI

Strategy research unit

The Institute of Energy Economics, Japan

Case study of Japan's H_2 import

- We revied the NEDO's study report from 2014 to 2017.
- The study assumed Japan will import hydrogen and consume it as a fuel for power generation or vehicle.

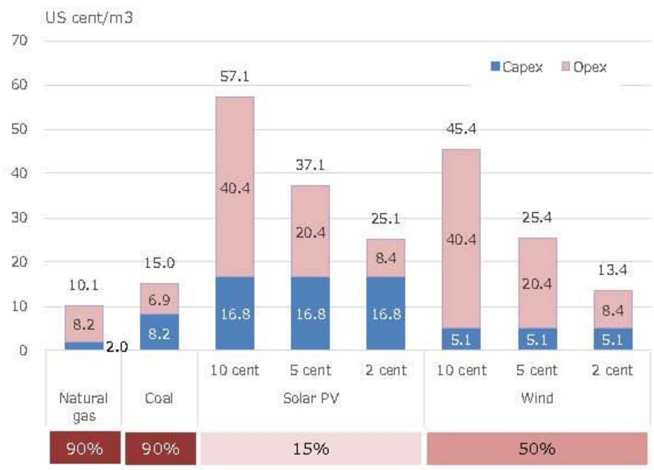


FCV = fuel-cell vehicle, LH2 = liquified hydrogen, MCH = Methylcyclohexane, NH3 = ammonia
Source: ERIA (2020)

1

H_2 production

- It resulted that steam reforming of natural gas is the lowest cost technology to produce commercial scale hydrogen.
- Cost of feedstock and capacity factor of a plant has significant impact.



Capacity factor of a plant

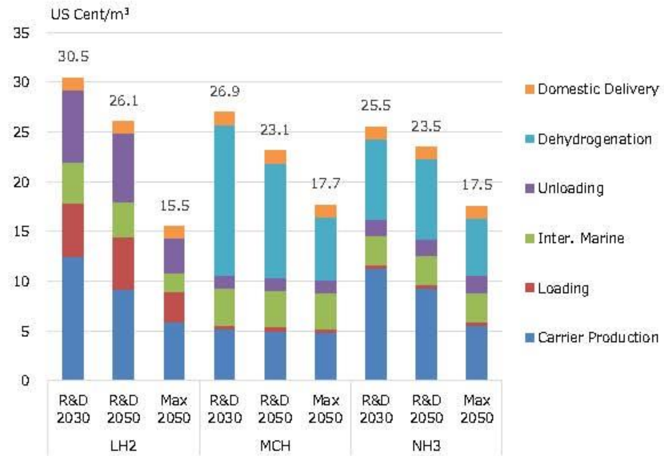
Cost of producing hydrogen

Natural gas price = $5/MMBtu
Coal price = not disclosed
Electricity price for water electrolysis = 10 cent/5 cent/2 cent
Source: ERIA (2020)

2

H_2 for power 1

- Economics of scale affect much on delivery cost.
  - When the demand is smaller, NH_3 can be the lowest cost option.
  - When the demand become greater, LH_2 can be the lowest cost option.



Cost of delivering hydrogen

LN2 = liquified hydrogen
MCH = Methylcyclohexane
NH3 = ammonia
Source: ERIA (2020)

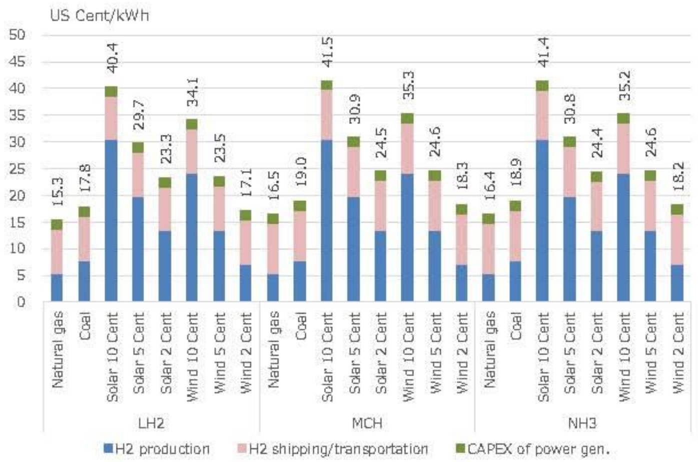
Hydrogen demand scenario

R&D 2030	Advance in R&D will reduce the cost of hydrogen in 2030, thereby initiating hydrogen demand.
R&D 2050	Advance in R&D will further reduce the cost of hydrogen in 2050, thereby stimulating hydrogen demand.
Max 2050	Competitive hydrogen cost will maximize hydrogen demand.

3

H_2 for power 2

- Hydrogen production cost determine total cost, while CAPEX of power plant has marginal effect.
- Share of shipping/transportation cost become larger when total cost become smaller.



Cost of generation electricity from hydrogen CCGT

Electricity price for household is approx. US cent 25/kWh in Japan.

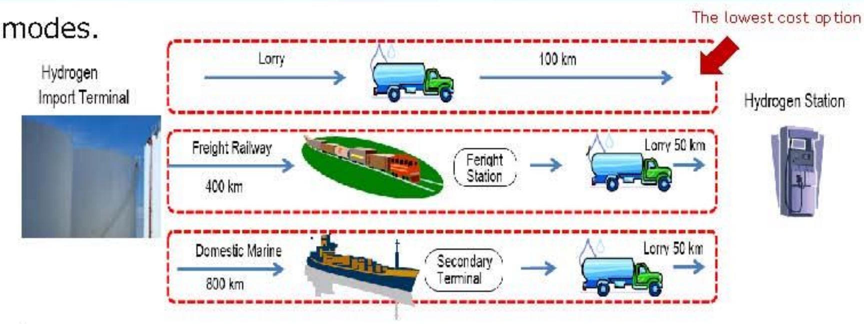
LCOE of thermal power generation is approx. US cent 8-10/kWh in Japan.

Demand = Max2050 scenario

LN2 = liquified hydrogen
MCH = Methylcyclohexane
NH3 = ammonia
Source: ERIA (2020)

H2 for vehicle 1

- 3 delivery modes.



- 3 demand sizes.

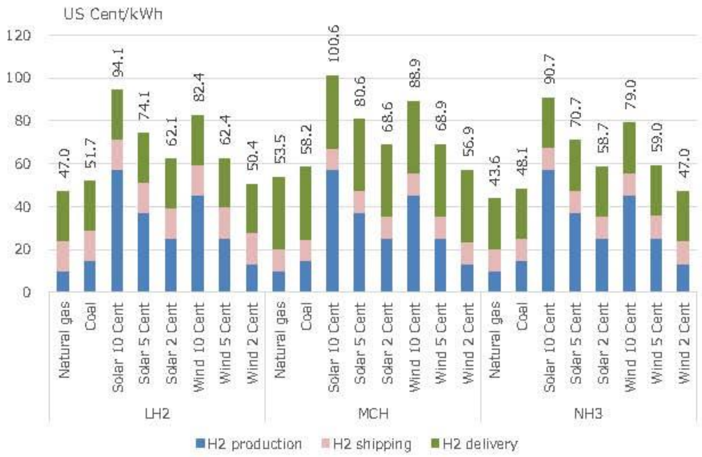
The lowest cost option

	Scenario		
	Small	Medium	Large
Hydrogen sales	300 Nm³/h	Ave. 830 Nm³/h Max. 1,200 Nm³/h	Ave. 1,240 Nm³/h Max. 2,400 Nm³/h
(Gasoline sales equivalent)	(100 KL/month)	(200 KL/month)	(300 KL/month)
Number of visitors (Peak hour)	8 vehicles/h 2 dispensers	15 vehicles/h 3 dispensers	22 vehicles/h 4 dispensers
Number of visitors (Monthly)	4,000 vehicles	8,000 vehicles	12,000 vehicles

H_2 for vehicle 2

- Hydrogen delivery cost (*) has significant impact in many cases.

* Delivery cost = transporting hydrogen carrier from the hydrogen import terminal to the hydrogen station, storing it, reproducing hydrogen from the carrier, and sending it to dispenser.



Hydrogen supply cost at a dispenser

Delivery mode = 100km by a lorry tank
Demand = Large scenario

LN2 = liquified hydrogen
MCH = Methylcyclohexane
NH3 = ammonia
Source: ERIA (2020)

Gasoline price ≒ US cent 14/kWh
Diesel price ≒ US cent 10/kWh
in Japan.

Fuel economy of FCEV is approx. 1.8 times better than ICE vehicle.

6

Conclusion

- Imported hydrogen is expensive compared to existing energies.
- Hydrogen can be a competitive fuel for power generation if a country can produce it in the country.
- Technological break through to reduce delivery cost is needed to make hydrogen an economical choice for vehicle fuel.
- Further reduction of production cost and shipping cost is needed to create hydrogen market.
- Policies help create a virtuous cycle of increasing demand and reducing costs.

7

Thank you!

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NEDO, Total System Introduction Scenario Research, Leading Technology Research and Development Project on Hydrogen Utilization (2016-2017)

We provide part of our cutting-edge research results on energy and the environment on our website free of charge.

IEEJ Website
http://eneken.ieej.or.jp/

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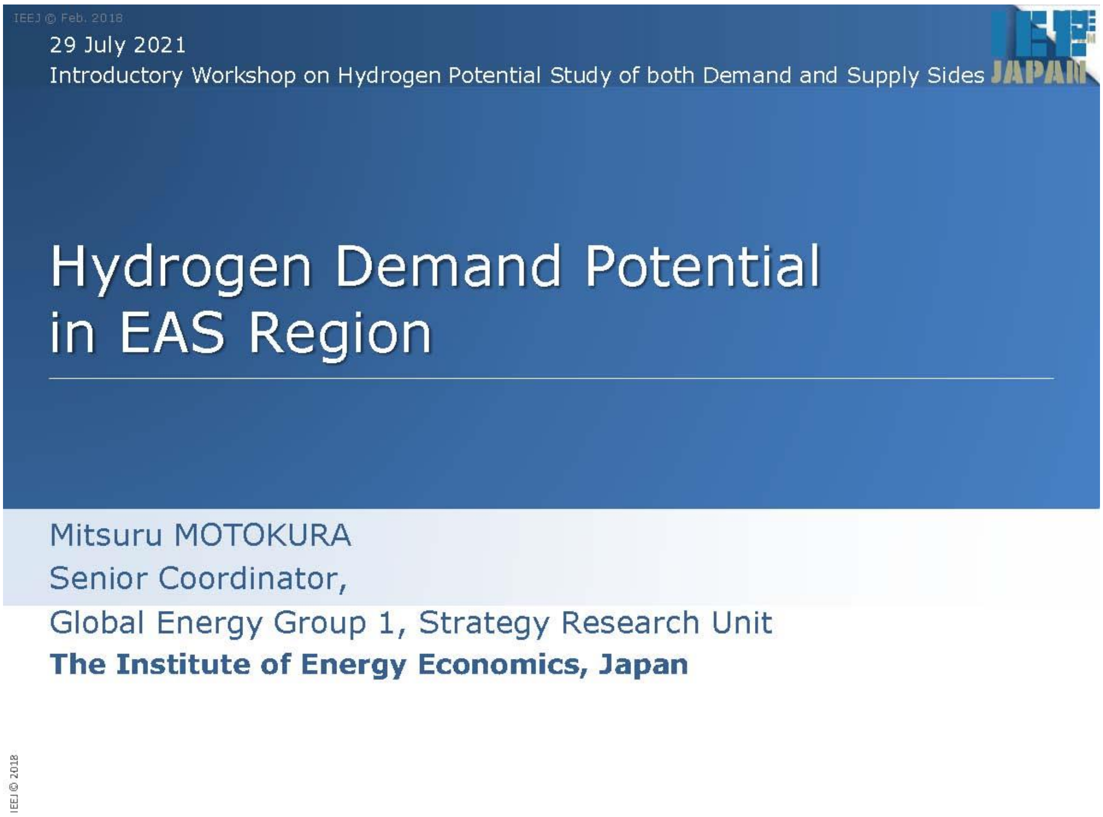
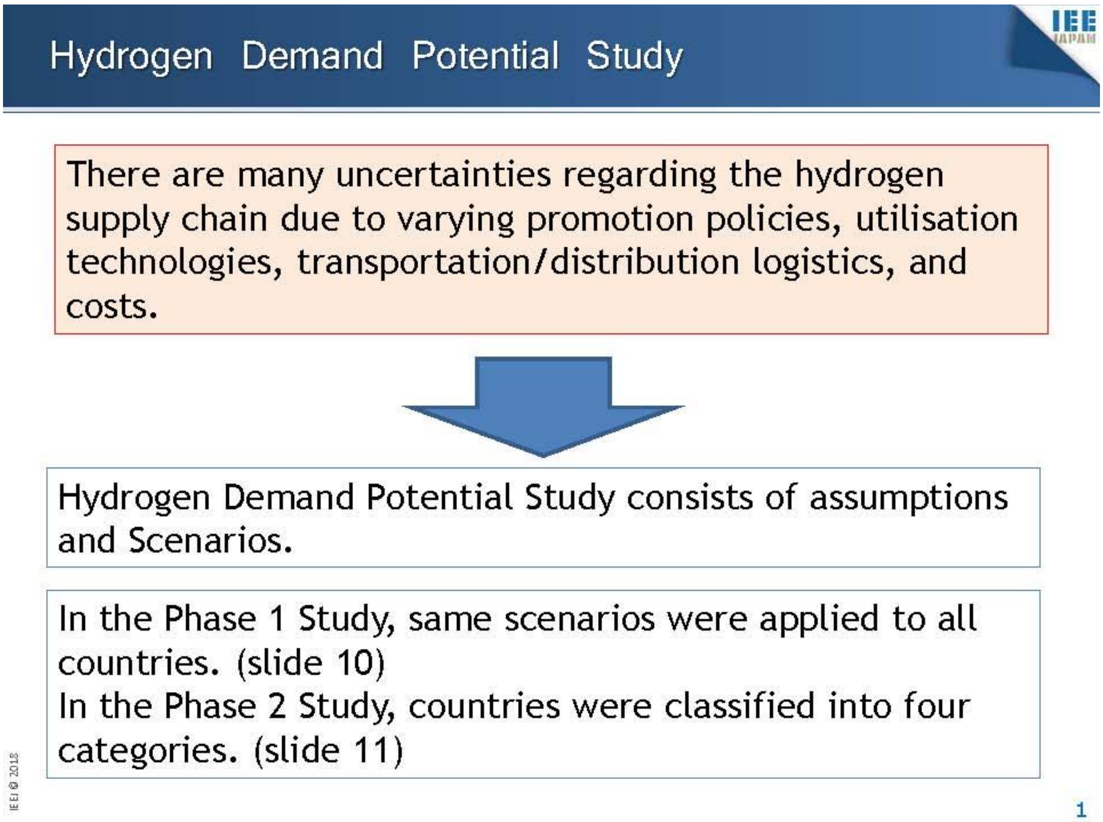
IEA 2020b	IEA, World Energy Outlook 2020
IEA 2020c	IEA, CO2 emission from fuel combustion 2020
Iseki 2012	ISEKI Takaya, Membrane Reformer for Energy Efficient Hydrogen Production, 2012
JST 2019	JST, Economics and CO2 emission of hydrogen and ammonia produced from coal gasification, December 2019
NOAA 2021	NOAA, Global Gas Flaring Observed from Space, access in May 2021
World Bank 2021	The World Bank, Global Gas Flaring Reduction Partnership, access in May 2021

3. Session 3: Hydrogen Demand Potential in the East Asia Summit Region by IEEJ





Basic assumption

- Nation wide H_2 **pipeline** is only partially established in 2040 as well as H_2 **refueling stations.**
- Ammonia, which is hydrogen carrier, for combustion purpose is excluded in this study as well as hydrogen for generating ammonia and/or methanol.
- Commercialized and prevailed H_2 technologies in 2040
  - H_2 and Natural gas mixed fuel gas turbine
  - H_2 and natural gas mixed fuel large scale boiler
  - Passenger Fuel Cell Vehicle (PFCV)
  - Fuel Cell Bus (FCB)
  - Fuel Cell Train (FCT)

Not prevailed technology in 2040

- Utility scale FC
- FC-Heavy-Duty-Vehicle
- FC-Ship (Technically available, but international and domestic refueling infrastructures will only be partially established in 2040.)

Note: Distributed FC system is not included in this study, because hydrogen would not be supplied directly unless hydrogen pipeline will be realized. Hydrogen for distributed FC system would be produced from on-site natural gas reforming, thus fuel demand for distributed FC system is categorized to "natural gas demand".

Scenario (Phase 1)

Sector	Fuel		Scenario 1	Scenario 2	Scenario 3
			H2 concenteration of mixed fuel		
Electricity generation	Coal	20% of new Coal-fired electricity generation (TWh) will be converted to Natural gas and H2 mixed fuel-fired generation	H2: 10% Nat gas: 90%	H2: 20% Nat gas: 80%	H2: 30% Nat gas: 70%
Electricity generation	Natural gas	20% of new Natural Gas-fired electricity generation (TWh) will be converted to Natural gas and H2 mixed fuel-fired generation			
Indistry	Natural gas	20% of Natural gas consumption for Industrial purpose will be replaced by Natural gas andH2 mixed fuel.			
			Share of H2/Gasoline		
Transport	Gasoline	Passenger Fuel Cell Vehicle: Gasoline demand will be converted to H2	OECD H2: 2.0% Gasoline: 98% Non-OECD H2: 1.0% Gasoline: 99%	OECD H2: 10% Gasoline: 90% Non-OECD H2: 5% Gasoline: 95%	OECD H2: 20% Gasoline: 80% Non-OECD H2: 10% Gasoline: 90%
			Sahre of H2/Diesel for Transport (Total)		
Transport	Diesel	Fuel Cell Bus: Diesel demand will be converted toH2	Japan H2: 0.05% Diesel: 99.95% Other countries H2: 0.025% Diesel: 99.975%	Japan H2: 0.1% Diesel: 99.9% Other countries H2: 0.05% Diesel: 99.95%	Japan H2: 0.2% Diesel: 99.8% Other countries H2: 0.1% Diesel: 99.9%
			Sahre of H2/Diesel for Transport (Rail Transport)		
Transport	Diesel	Fuel Cell Train: Diesel consumption for Rail Transport will be converted to H2	H2: 5% Diesel: 95%	H2: 10% Diesel: 90%	H2: 20% Diesel: 80%

Classification of Countries (Phase 2)

Future hydrogen demand in a country is likely to be greatly affected by the balance between the hydrogen supply cost and the income level of a country.

		Hydrogen Supply Cost	
		Cheap	Expensive
Income Level	High	A The hydrogen supply costs are low, and the income levels are high. **The most widespread use of hydrogen can be expected.** Australia Brunei Darussalam Indonesia **Malaysia (Sabah and Sarawak)** New Zealand	B The hydrogen supply costs are high, and the income levels are high as well. **The use of hydrogen can be expected through a hydrogen promotion policy.** China Japan Korea **Malaysia (Peninsula)** Singapore Thailand
	Low	C The hydrogen supply costs are low, and the income levels are low as well. **The use of hydrogen is limited. Becomes a hydrogen exporter.** India Lao PDR Myanmar	D The hydrogen supply cost is high, and the income level is low. Hydrogen demand is unlikely to be expected. Cambodia Philippines Viet Nam

Malaysia is divided by generation capacity in the Electricity Generation Sector and state GDP (2018) in the Transport Sector.

Scenario (Phase 2)

Quadrant A

Sector	Assumption	Conversion Ratio
Electricity generation	Full-scale hydrogen use will begin in 2030 (Assume that 10 years will be required to build a large-scale hydrogen production plant, domestic supply infrastructure, and hydrogen-fired CCGT.) Hydrogen will be supplied to the power plant through newly constructed hydrogen pipelines.	The ratio of conversion to hydrogen and natural gas mixed fuel or pure hydrogen. 50%
	Existing natural gas power generation (TWh) as of 2030 will be partially converted to the 30% hydrogen and 70% natural gas mixed fuel by replacing the combustors.	
	New natural gas power generation (TWh) after 2030 will be partially converted to the 100% hydrogen fuel.	
Transport	Assume a certain share of the zero-emission vehicle (ZEV) in the registered passenger cars in 2040. Fuel cell vehicle (FCV) share in ZEV: 20%	The ratio of ZEV 50%

Scenario (Phase 2)

Quadrant B-1

Sector	Assumption	Conversion Ratio
Electricity generation (Existing generation)	Full-scale hydrogen use will begin in 2030 (Assume that 10 years will be required to build a large-scale hydrogen production plant, domestic supply infrastructure, and hydrogen-fired CCGT.) Japan, the Republic of Korea, Malaysia (Peninsula), Singapore, and Thailand are assumed to construct hydrogen import terminals adjacent to liquefied natural gas (LNG) import terminals for power generation. Other than Singapore, existing gas pipelines will be used to distribute hydrogen in a country. If gas power plants are connected to the same gas pipeline network, they will be converted to hydrogen at once.	The ratio of conversion to hydrogen and natural gas mixed fuel or pure hydrogen
	Existing natural gas-fired electricity generation (TWh) as of 2030 will be partially converted to the 30% hydrogen and 70% natural gas mixed fuel by replacing the combustors.	
	Malaysia (Peninsula) Imported hydrogen.	50%
	Thailand Gas power plants connected to LNG import terminals will be converted. The gas power plants in the following two areas are not subject to conversion: The south eastern area that receives natural gas from the JDA with Malaysia, – The north-western area that natural gas is imported from Myanmar.	50%
	China China will have a mix of domestic fossil–fuel reformed hydrogen and imported hydrogen.	50%
	Japan Imported hydrogen	50%
	Korea The KOGAS high-pressure gas pipeline connected to the gas-fired plants is looped.	100%
	Singapore The country is small. It is assumed that new hydrogen pipeline will be constructed. The number of gas-fired plants may be very small.	100%

Scenario (Phase 2)

Quadrant B-2

Sector	Assumption	Conversion Ratio
Electricity generation (New generation)	**New** natural gas power generation (TWh) after 2030 will be partially converted to the 100% hydrogen fuel. Japan,Korea Singapore, and Thailand are assumed to construct new 100% hydrogen thermal power adjacent to the hydrogen import terminals, which will not be connected to the existing natural gas pipelines. China will have a mix of domestic fossil fuel–reformed hydrogen and imported hydrogen.	
	Malaysia (Peninsula) **Thailand** **China** **Japan** **Republic of Korea**	50%
	Singapore The number of gas-fired plants may be very small.	100%
Transport	Assume a certain share of the zero-emission vehicle (ZEV) in the registered passenger cars in 2040. FCV share in ZEV: 10%	The ratio of ZEV 30%

Scenario (Phase 2)

Quadrant C

Sector	Assumption	Conversion Ratio
Electricity generation	Full-scale hydrogen use will begin in 2040 (assume it will take 20 years to improve income levels) Hydrogen is supplied to the power plant through newly constructed hydrogen pipelines.	The ratio of conversion to mixed fuel
	Existing natural gas–fired electricity generation (TWh) as of 2030 will be partially converted to the 30% hydrogen and 70% natural gas–mixed fuel by replacing the combustors except for the Lao PDR that has no plan of introducing natural gas–fired plant.	30%
	A new 100% hydrogen-fired plant will be operated in 2040 except for the Lao PDR. The generation capacity is assumed to be 200 MW.	One 200 MW plant
Transport	Assume a certain share of the zero-emission vehicle (ZEV) in the registered passenger cars in 2040. FCV share in ZEV: 10%	The ratio of ZEV 30%

Scenario (Phase 2)

Quadrant D

Sector	Assumption	Conversion Ratio
Electricity generation	Full-scale hydrogen use will begin in 2040 (Assume it will take 20 years to improve income levels). As of 2040, a pilot project or first plant will be introduced. Assume that a hydrogen import terminal will be constructed adjacent to the liquefied natural gas (LNG) terminal that is expected to be developed in the future. Cambodia will also consider importing hydrogen from the Lao PDR through pipelines.	
(Existing generation)	Existing natural gas power generation (TWh) as of 2030 will be partially converted to the 30% hydrogen and 70% natural gas mixed fuel by replacing the combustors.	
	Viet Nam	30%
	Cambodia **Philippines** The number of gas-fired plants may be very small.	100%
(New generation)	No new 100% hydrogen-fired plant will be operated in 2040.	-
Transport	Assume a certain share of the zero-emission vehicle (ZEV) in the registered passenger cars in 2040. FCV share in ZEV: 5%	The ratio of ZEV 30%

Major Differences of Scenarios (Phases 1 and 2)

Sector	Item	Phase 1	Phase 2
Electricity generation	Subject of fuel switch	Natural gas Coal	Natural gas
	Scenario (Factors of change)	Fuel for electricity generation: The hydrogen concentration in natural gas and hydrogen mixed fuel	Generated electricity: The conversion ratio of generated electricity to hydrogen/natural gas mixed fuel or pure hydrogen
Industry	Subject of fuel switch	Natural gas	Excluded
Transport	Mode	Passenger fuel cell vehicle (gasoline) Fuel cell bus (diesel) Fuel cell train (diesel)	Passenger fuel cell vehicle (gasoline)
	Scenario	Conversion ratio of gasoline/diesel	The ratio of zero-emission vehicle

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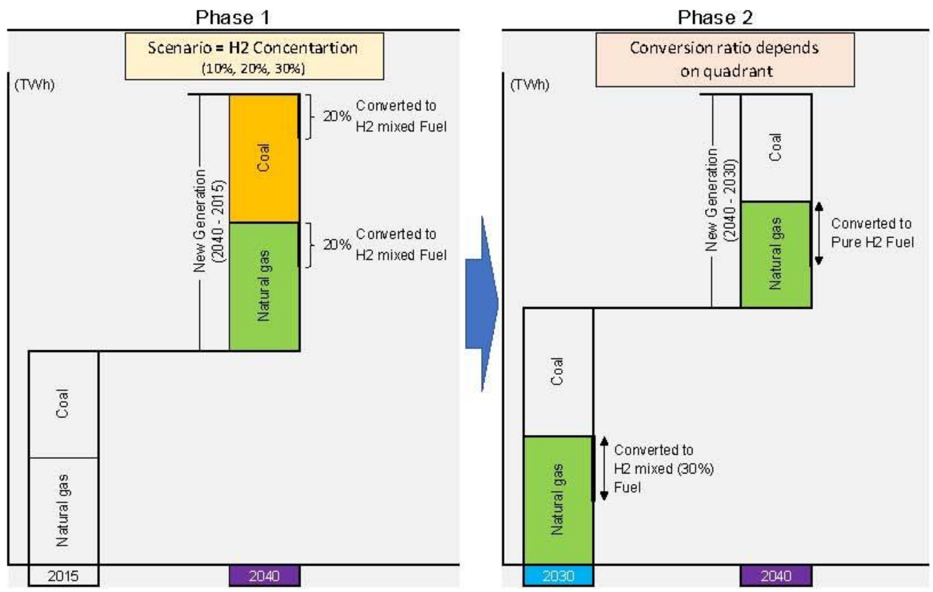
Comparison of Scenarios (Phase 1 & 2)

Sector: Electricity Generation

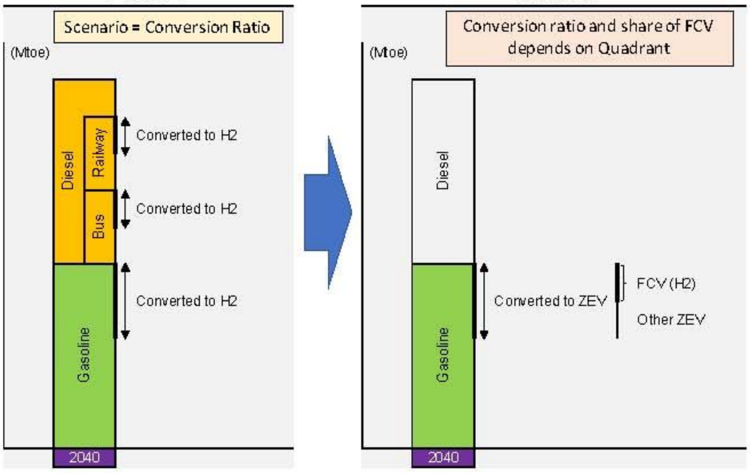


Note; Coal was excluded in the Phase 2 Study.

11

Comparison of Scenarios (Phase 1 & 2)

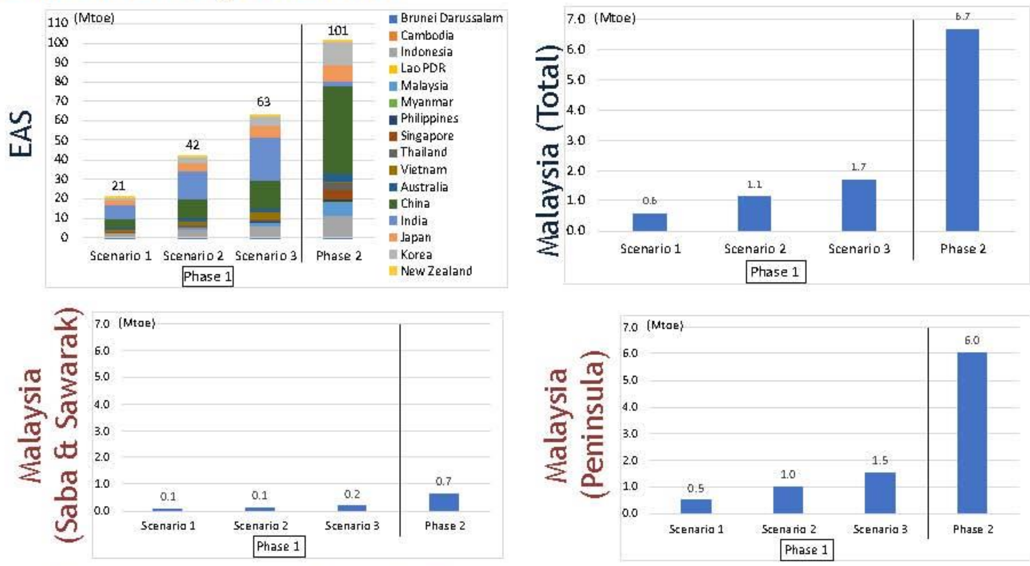
Sector: Transport



Note; Diesel was excluded in the Phase 2 Study.

Hydrogen Demand Potential

Sector: Electricity Generation

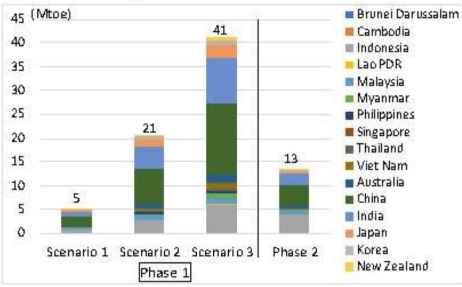


China will have the largest Potential in EAS region.
Compared to the Phase 1 Study, the Potential of Malaysia will increase in the Phase 2 Study because the scenario of Natural gas generation conversion was aggressive.

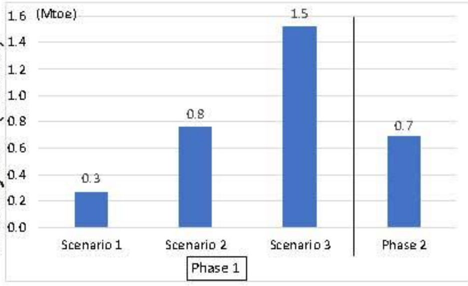
Hydrogen Demand Potential

Sector: Transport

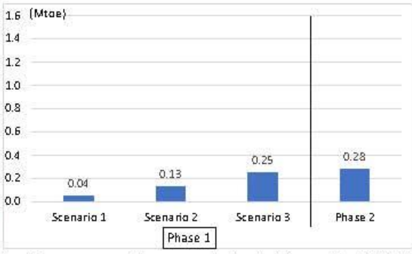
EAS



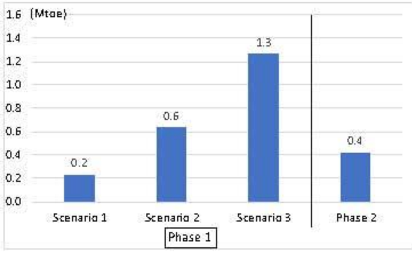
Malaysia (Total)



Malaysia (Saba & Sawarak)



Malaysia (Peninsula)



Note; Some corrections are included from the ERIA Phase 2 Report.

China and Indonesia will have the largest Potential in EAS region.
Compared to the Phase 1 Study, the Potential of Malaysia will decrease in the Phase 2 Study because Diesel is excluded.

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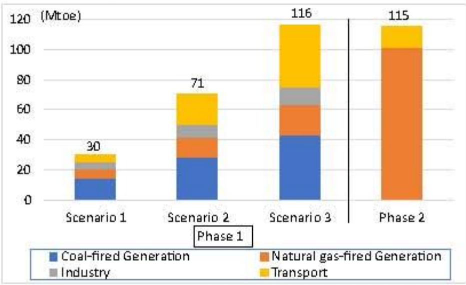
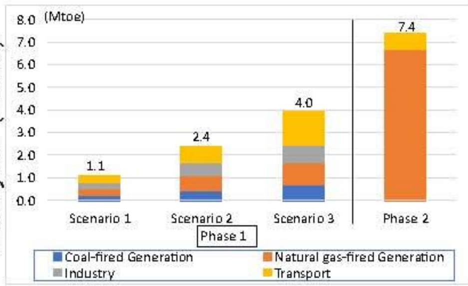
Hydrogen Demand Potential

Sector: Total

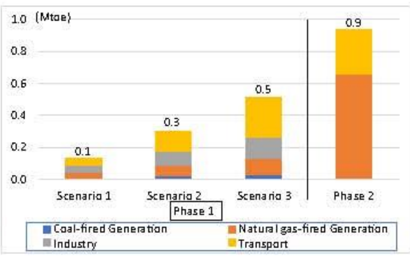
EAS



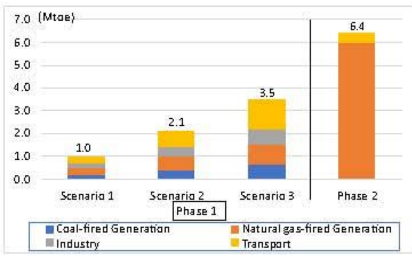
Malaysia (Total)



Malaysia (Saba & Sawarak)



Malaysia (Peninsula)



Note; Some corrections are included from the ERIA Phase 2 Report.

In the Phase 2 Study, Coal-fired electricity generation and Industry sector were excluded.

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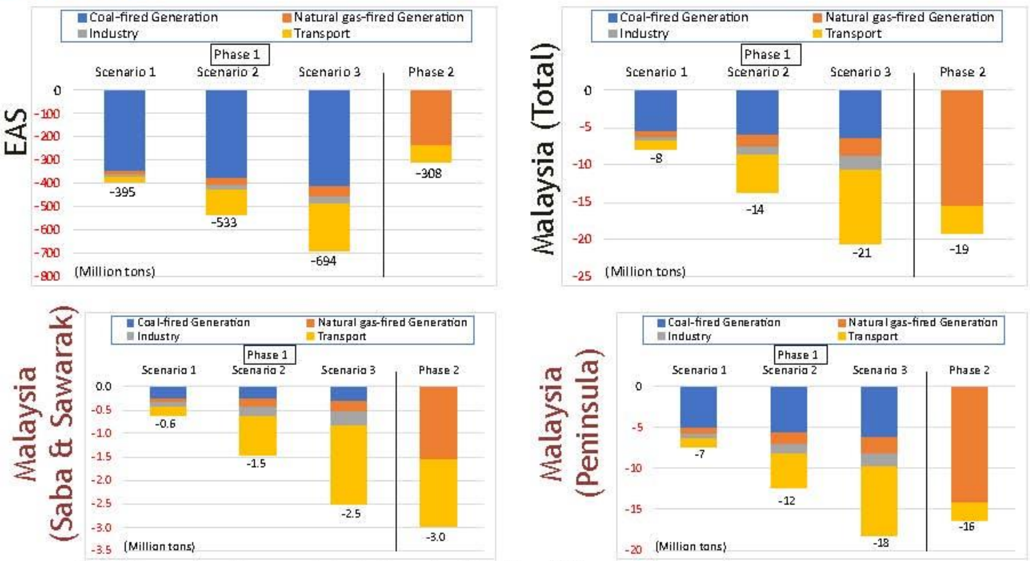
CO_2 Emission Reduction

Sector: Total



Note; Some corrections are included from the ERIA Phase 2 Report.

Compared to the Phase 1 Study, CO2 Emission Reduction will be decrease because Coal was excluded in the Phase 2 Study, despite aggressive assumption of conversion from Natural gas electricity generation.

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Appendix

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Calculation of Hydrogen Demand Potential (Electricity generation sector)

Baseline: Electricity Generation Outlook

TWh

Country	EAS			Malaysia		
Fuel	2015	2030	2040	2015	2030	2040
Coal	6,210	8,791	10,745	63	103	146
Oil	184	104	83	2	2	2
Natural gas	*1,173*	*2,083*	*3,003*	***70***	***134***	***191***
Nuclear	382	1,193	1,352	0	0	0
Hydro	1,510	1,945	2,126	14	24	24
Geothermal	31.7	46.8	64.4	0.0	0.0	0.0
Others	500	1,765	2,494	1	6	6
Total	9,883	15,928	19,868	150	268	368

Source: ERIA Energy Outlook 2019

Natural gas generation:
Divided by generation capacity
Saba & Sawarak: 10%
Peninsula : 90%

Assumption of Thermal Efficiency and Hydrogen Specification

Thermal efficiency*1	Coal: 55% Natural gas: 63% Hydrogen: 63%
Hydrogen specification*2	Gas density: 0.0835 kg/m^3 Net calorific value: 10,780 kJ/m^3 = 2,575 kcal/m^3 = 30,834 kcal/kg = 3,884 m^3/toe

Source: *1 High Efficiency of Thermal Power, November 2017, Agency for Natural Resources and Energy, Ministry of Energy, Trade, and Industry (Japanese only).
*2 Iwatani Corporation.

Calculation of Hydrogen Demand Potential (Transport sector)

In order to calculate the hydrogen demand potential, it must be assumed the differential of mileage between conventional internal combustion engine car and FCV although very limited information. We select TOYOTA CROWN as internal combustion engine car and TOYOTA MIRAI as FCV because dimensions are similar.

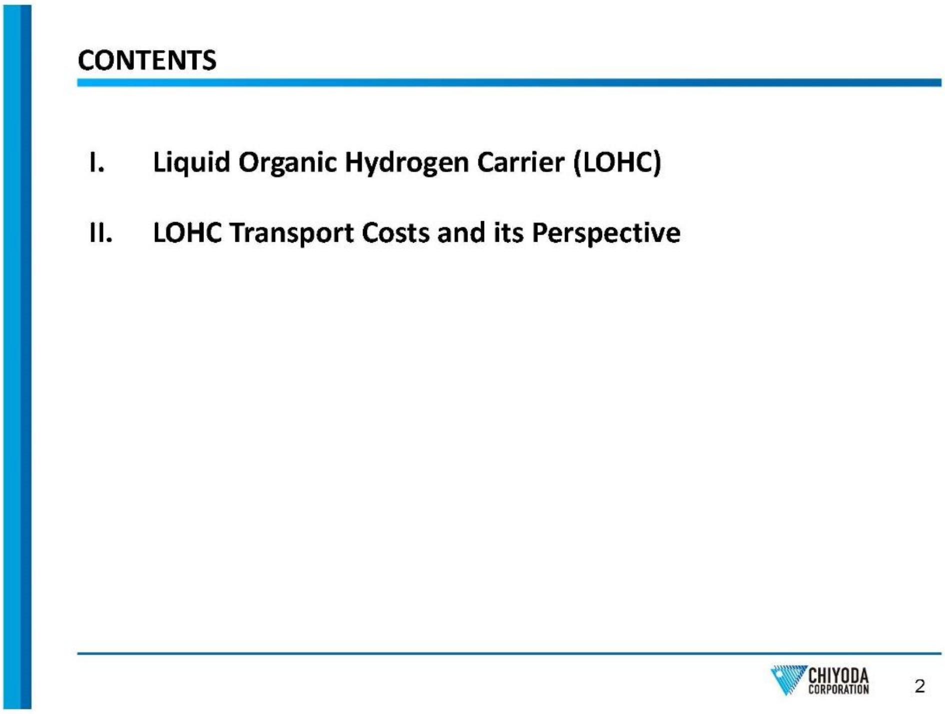
We assume that the fuel mileage of FCV is **1.8** times better than internal combustion engine car.

Comparison between TOYOTA CROWN and TOYOTA MIRAI

	CROWN	MIRAI
Appearance		
Dimensions (cm) Length Width Height	4,910 1,800 1,455	4,890 1,815 1,535
Weight (kg)	1,590–1,650	1,850
Displacement	2,000 cc	-
Fuel mileage (JC08 mode)	12.8 km/ litre (16,372 km/ toe)	7.59 km/ m3 (29,480 km/ toe)
	MIRAI's fuel mileage is **1.8** times better	

Thank you for your attention!

4. **Session 4: Introduction of Hydrogen Transport Costs (Liquefied Hydrogen) by Chiyoda Corporation**



I. Liquid Organic Hydrogen Carrier (LOHC)

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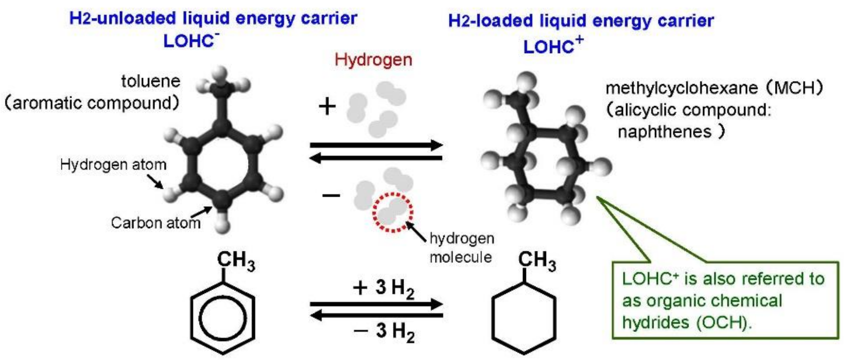
Liquid Organic Hydrogen Carrier (LOHC)

- The hydrogen energy storage solution is based on two separate processes, namely the loading (hydrogenation) and unloading (dehydrogenation) of a liquid energy carrier.
- An important advantage of the hydrogen being chemically bonded to the liquid carrier is that it can be stored under ambient temperature and pressure without suffering any self-discharge or the loss of hydrogen.



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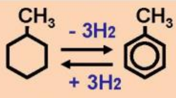
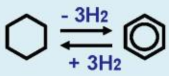
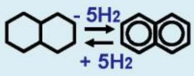
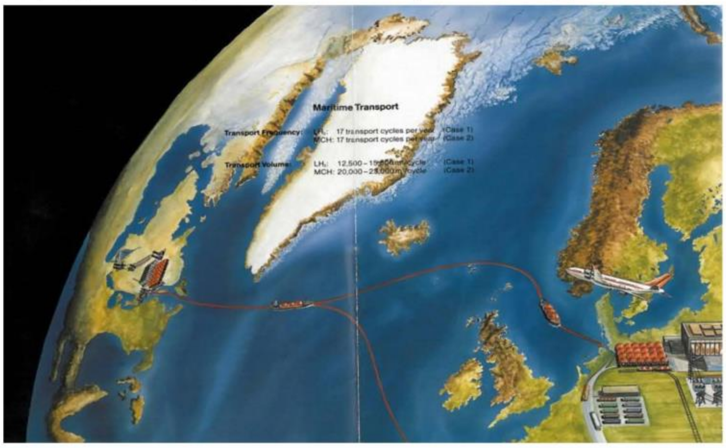
Liquid Organic Hydrogen Carrier (LOHC) : Several types

	MCH−Toluene		Cyclohexane −Benzene		Decaline−Naphthalene	
	MCH	Toluene	Cyclohexane	Benzene	Decaline	Naphthalene
Molecular formula	C_7H_{14}	C_7H_8	C_6H_{12}	C_6H_6	$C_{10}H_{18}$	$C_{10}H_8$
Chemical equation	 ⊿H = 205 kJ/mol		 ⊿H = 206 kJ/mol		 ⊿H = 332 kJ/mol	
Molar mass(g/mol)	98.2	92.1	84.2	78.1	138.3	128.2
Phase @RT	**Liquid**	**Liquid**	**Liquid**	**Liquid**	**Liquid**	**Solid**
Density(g/cm^3)	0.77	0.87	0.78	0.87	0.90	0.98
Melting point (deg.C)	**-127**	**-95**	**7**	**6**	Cis:**-43** Trans:**-30**	**80**
Boiling point (deg.C)	101	111	81	80	Cis:195 Trans:186	218
H_2 store (wt%)	6.2	–	7.2	–	7.3	–
density (kg-H_2/m^3)	47	–	56	–	65	–

Liquid Organic Hydrogen Carrier (LOHC) : EQHHPP

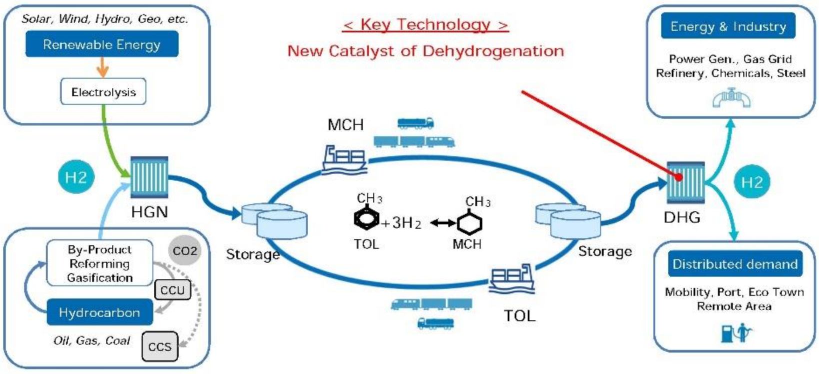
- The Euro-Québec Hydro-Hydrogen Pilot Project (EQHHPP) was started in 1989 and the pilot project examined the feasibility of transporting hydrogen across the Atlantic.
- In this project, MCH has also been studied in addition to the LH2 and NH3, however, technology of dehydrogenation catalyst has not been matured yet and been stopped its development.



(Source) EQHHPP

MCH Hydrogen Supply Chain Overview

- Chiyoda has established a large and efficient H_2 storage and transportation system.
- Methylcyclohexane (MCH), an H_2 carrier, remains a liquid under normal temperature and pressure.



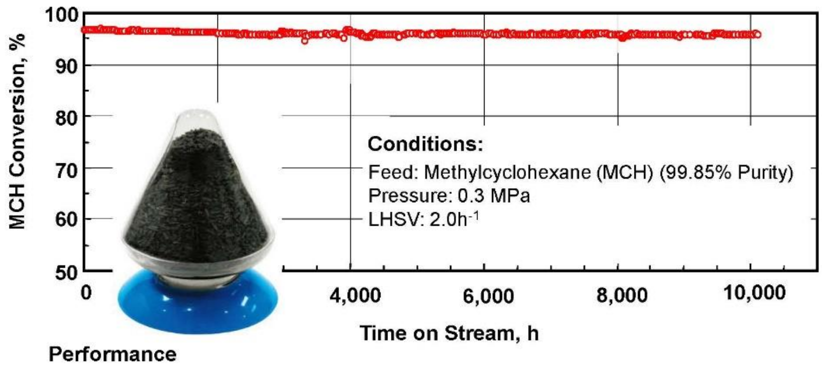
Key Features of MCH Hydrogen Technology

Long term storage & long distance transportation	Chemically stable, minor MCH (H_2) loss during long term storage and long distance transportation
Easy to handle	Liquid under ambient temperature and pressure Approximately 1/500 in volume
Use of existing oil infrastructure	Utilize existing infrastructure, standard, regulation, to minimize social investment for H2 introduction
Storage and transportation risk equivalent to petroleum products.	Safe storage and transportation that is equivalent level to petroleum products
Combination of new and proven technologies	Combination of conventional technology and new dehydrogenation catalyst technology

MCH Technology Development : Phase 1 (Laboratory)

- Chiyoda succeeded in developing a dehydrogenation catalyst at its R&D center in 2008 that has achieved optimum performance over 12,000 hrs continuous operation.

Dehydrogenation Catalyst Development in Yokohama



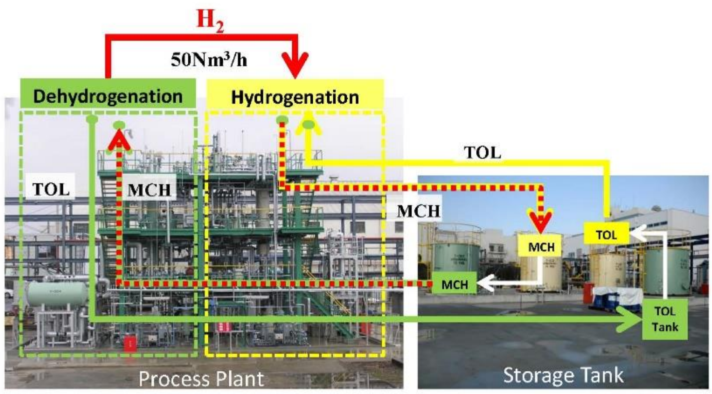
Performance

- **MCH conversion: >95%, Toluene selectivity; >99.9%, H_2 yield: >95%**
- **H_2 generation rate: >1,000 Nm^3-H_2/h/m^3-cat. (1,000 Ncm^3-H_2/h/cm^3-cat.)**
- **Catalyst life: >10,000hr**

MCH Technology Development : Phase 2 (Pilot Test)

- Chiyoda confirmed the performance and long life of the catalyst through 10,000 hours continuous operation of its pilot plant from April 2013 to November 2014

SPERA Hydrogen Demonstration Plant in Yokohama



MCH Technology Development : Phase 3 (Demonstration)

- Chiyoda and partners established the Advanced Hydrogen Energy chain Association for technology Development ("AHEAD") and initiated the world's first global hydrogen supply chain demonstration project

Description	
Scale	210 tons/year (maximum)
Duration	March 2020 - December 2020
Hydrogen Supply	Brunei Darussalam (Hydrogen Production)
Hydrogen Demand	Kawasaki City (fuel for gas turbine power plant)
Transportation	ISO tank container (container ship/truck)
Business Scheme	Establishment of the Association for Technology Development. NEDO Funded Project*

* Technology Development for the Realization of a Hydrogen Society (funded by NEDO)
"Demonstration of the Hydrogen Supply Chain by the Organic Chemical Hydride Method Utilizing Unused Energy"

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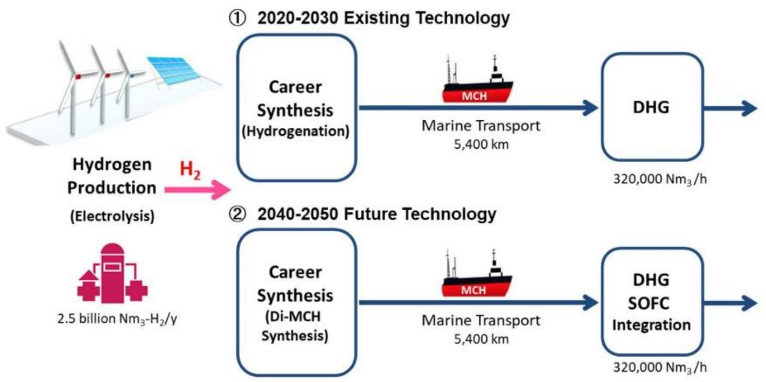
II. LOHC Transport Costs and its Perspective

Model of Global Hydrogen Supply Chain

- Two global hydrogen supply chain models are proposed to compare the hydrogen costs: 2020–2030 Existing Technology model (Existing model) utilizing existing technologies, and 2040–2050 Future Technology model (Future model) utilizing future advanced technologies

Model for Global Hydrogen Supply Chain



Model of Global Hydrogen Supply Chain : Future Technology

- The advanced technologies employed for the Future model are listed as follows.

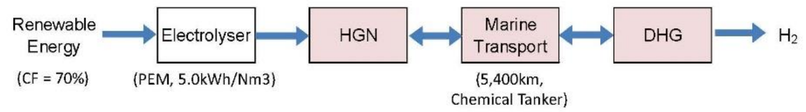
Future technologies:

- ✓ Process simplification, such as MCH direct synthesis (Tokyo University, 2019), employed as a substitute for the combination of electrolysis and hydrogenation (HGN)
- ✓ Transportation efficiency Improvement utilizing Super Eco Ship (NYK)
- ✓ Energy efficiency improvement of dehydrogenation by catalyst performance increase
- ✓ Heat integration optimization using SOFC exhaust gas to dehydrogenation heat

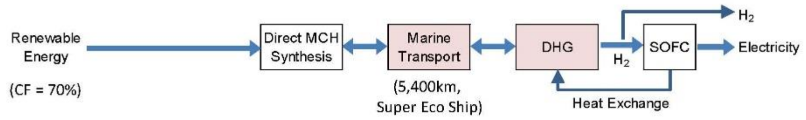
Model of Global Hydrogen Supply Chain : Key Assumptions

- In the 2020–2030, hydrogen is produced by PEM electrolysis, chemically fixed to toluene (hydrogenation), transported by chemical tankers and extracted by dehydrogenation.
- In the 2040–2050, renewable power will directly synthesize MCH, transported by Super Eco Ships, and hydrogen will be extracted in the dehydrogenation with SOFC exhaust heat.

1. 2020 – 2030 Existing Technology



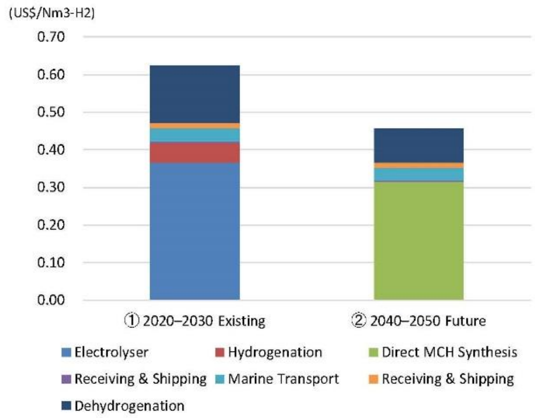
2. 2040 – 2050 Future Technology



Global Hydrogen Supply Chain Cost (US$0.05/kWh)

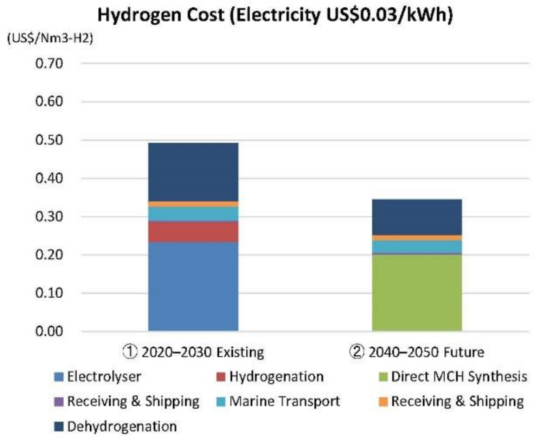
- At the electricity price of US$0.05/kWh, the hydrogen price in 2040–2050 is estimated to be reduced by around 25%, compared to US$0.62/Nm3 in 2020–2030.

Hydrogen Cost (Electricity US$0.05/kWh)



Global Hydrogen Supply Chain Cost (US$0.03/kWh)

- At the electricity price of US$0.03/kWh, the hydrogen price in 2040–2050 is estimated to be reduced by around 30%, compared to US$0.49/Nm3 in 2020–2030.



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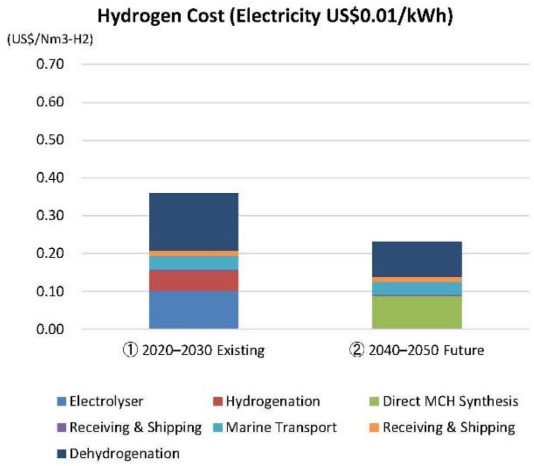
Global Hydrogen Supply Chain Cost (US$0.01/kWh)

- At the electricity price of US$0.01/kWh, the hydrogen price in 2040–2050 could be reduced to around US$0.23/Nm3, nearly 35% reduction, compared to existing model in 2020–2030.



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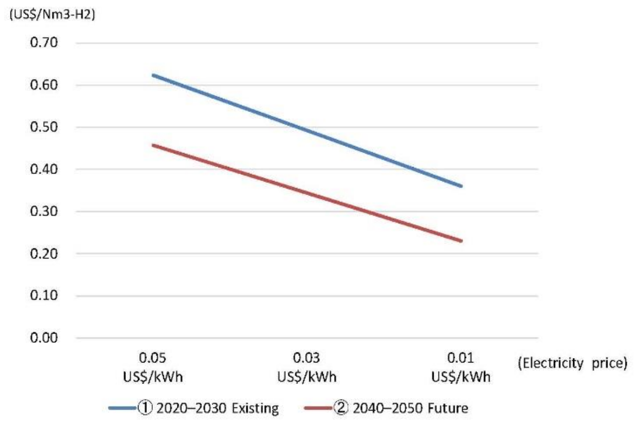
Global Hydrogen Supply Chain Cost : Summary

- The study showed that the total hydrogen supply chain cost could be reduced by around 20%–30% broadly owing to future technology improvements, like MCH direct synthesis, catalyst performance upgrades, and heat integration of SOFC exhaust gas to dehydrogenation.



Thank You

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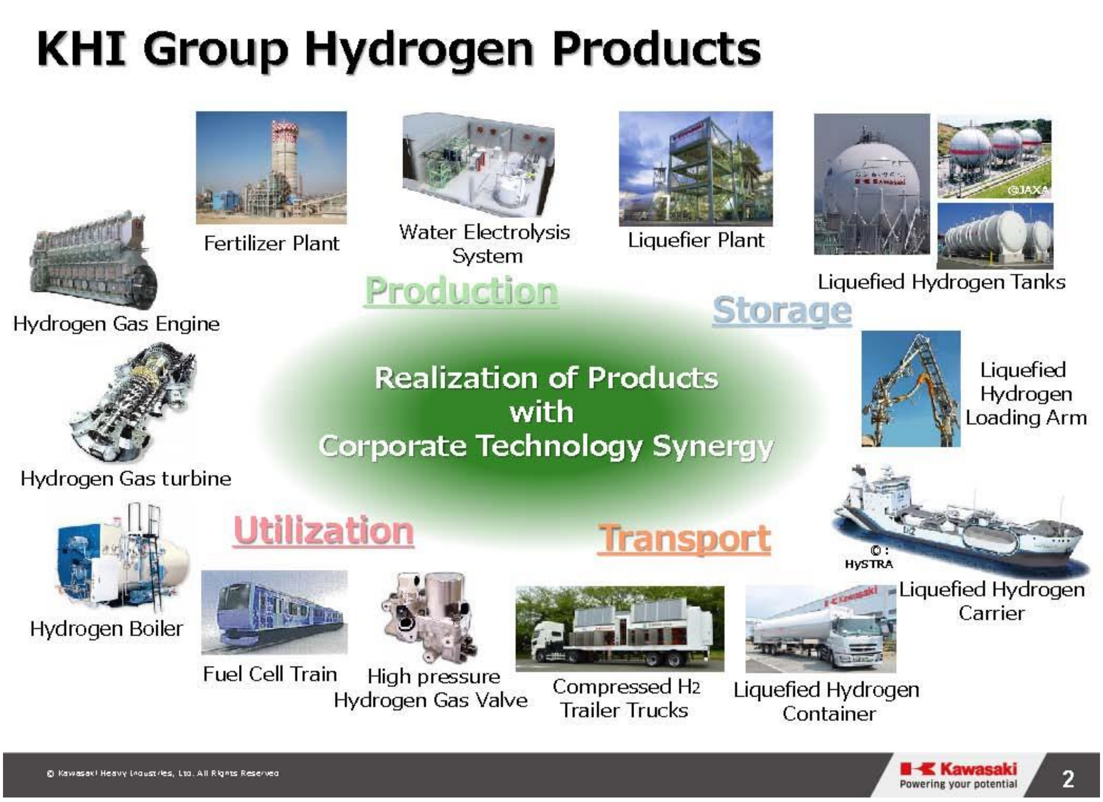
CHIYODA GROUP

5. **Session 5: Introduction of Hydrogen Transport Costs (Liquefied Hydrogen) by Kawasaki Heavy Industries**



Toward large volume hydrogen utilization essential for decarbonization

Energy system only with renewables and battery storage has a limit for energy scale, facility cost and applications.

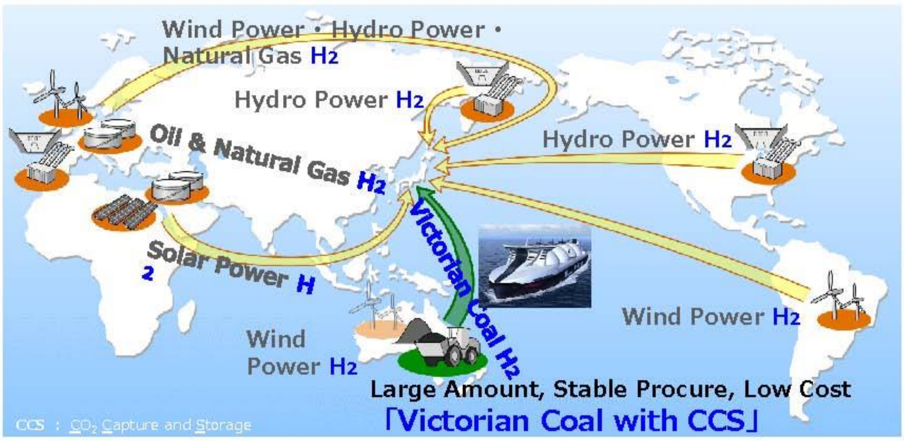
Liquefied hydrogen enables large amount, long-distance, long-term transportation and storage of energy and connects multiple sectors.

With extremely wide range of industries involved in hydrogen supply chain and demand field, hydrogen is highlighted worldwide due to creating a virtuous cycle for environment and economy.

Kawasaki Heavy Industries contributes to achievement of decarbonization as the sole company in the world that owns the whole hydrogen supply chain technology for production, transportation, storage and utilization.

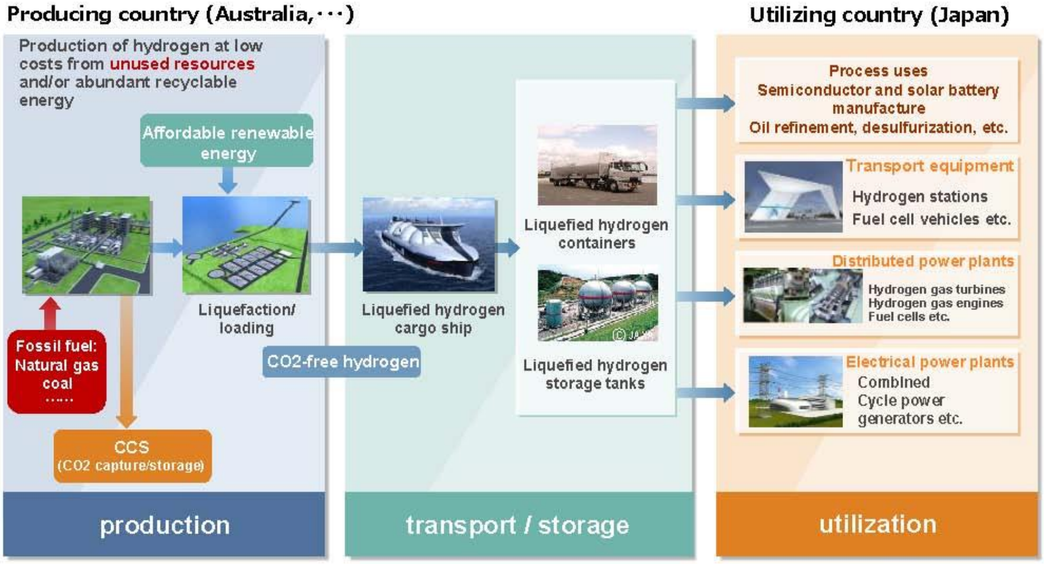
CO_2-Free Hydrogen Resources in the World

- Hydrogen can be produced from various sources and procured from many countries → Contribute to energy security
- Large amount, long-distance, long-term transportation and storage of energy and sector integration are possible with hydrogen → Contribute to resilience



Concept of CO_2-free Hydrogen Chains

Stable energy supply while suppressing CO2 emissions



Kawasaki Powering your potential

Liquefied Hydrogen
~ Large-scale Transport Methods for Hydrogen ~

- Extremely low temperature (-253 degrees C)
- 1/800 the volume of hydrogen gas
- Transport medium of proven practical use in industry and as rocket fuel
- Non-toxic, odorless and no greenhouse effect
- High purity = no need for refinement (can be supplied to fuel cells by evaporation alone)

Purity of liquefied hydrogen is enough high (99.999% or more) to meet the requirement for FCV fuel (99.97% or more)

*ISO14687-2 Hydrogen fuel product specification

Liquefied hydrogen tanks (Tanegashima Rocket Base)

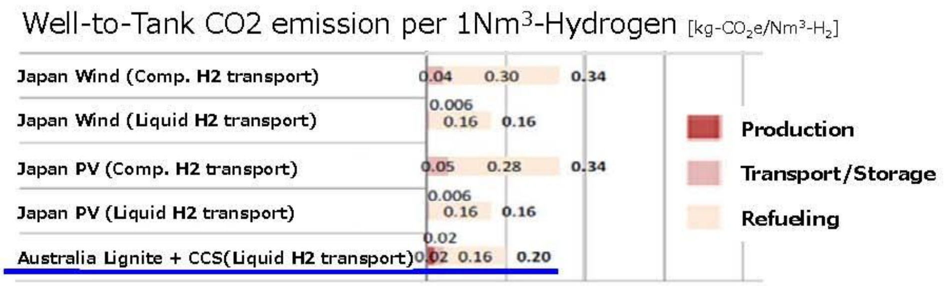
Largest liquefied hydrogen tanks in Japan (Kobe)

Commercial LH2 Carrier (Future)

Kawasaki Powering your potential

LCA by Mizuho Information & Research Institute

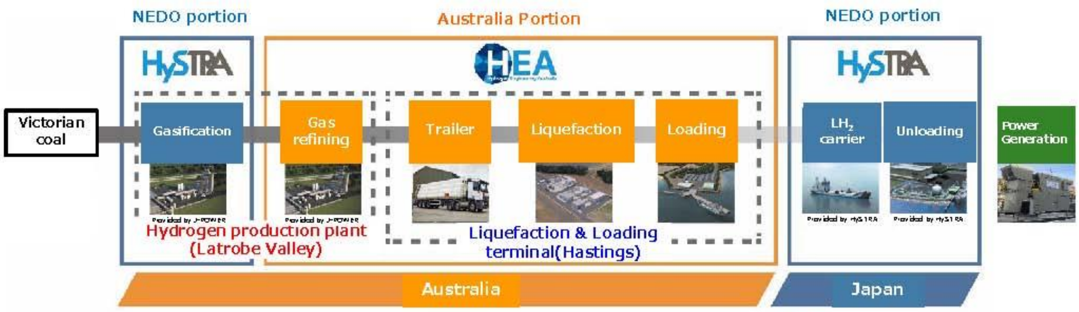
- Low CO2 emission equivalent to renewable oriented hydrogen



LCA by Mizuho Information & Research Institute
Ref: https://www.mizuho-ir.co.jp/publication/report/2016/pdf/wttghg1612.pdf

HESC Pilot Project Structure

Kawasaki is working with a number of partners on HESC Pilot Project supported by the governments of Japan and Australia.



CO2-free Hydrogen Energy Supply Chain Technology Research Association (HySTRA)

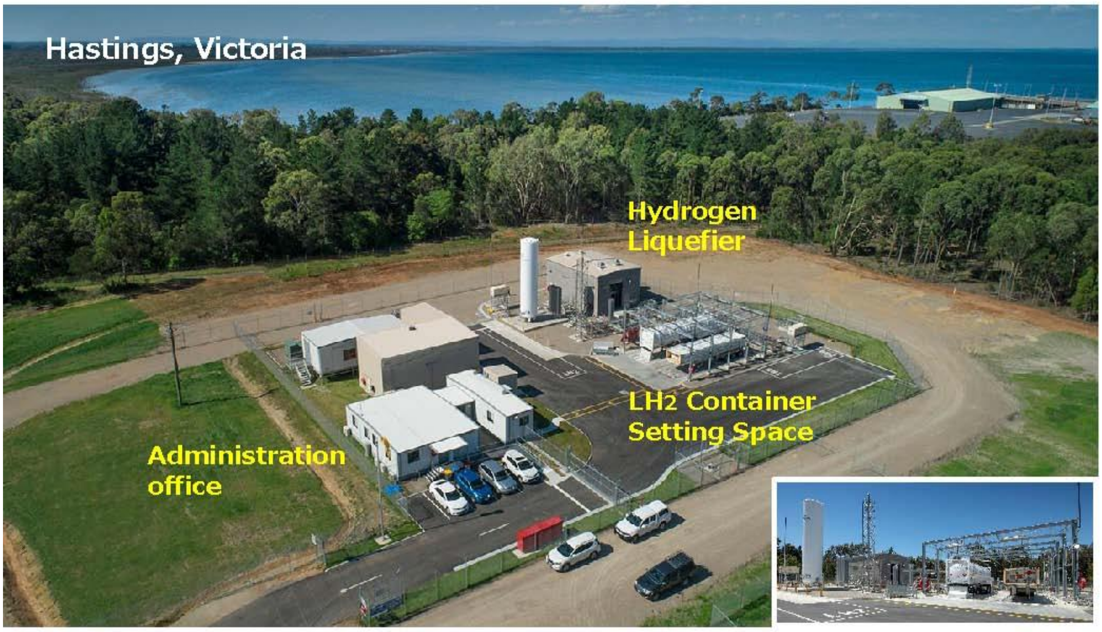
Kawasaki, Iwatani, J-Power, Shell Japan
Marubeni, ENEOS, KLINE
Supported by NEDO and METI

Hydrogen Engineering Australia (HEA)

Kawasaki, J-Power, J-Power Group, Iwatani
Marubeni, Sumitomo, AGL
Supported by Victorian and Australian Governments

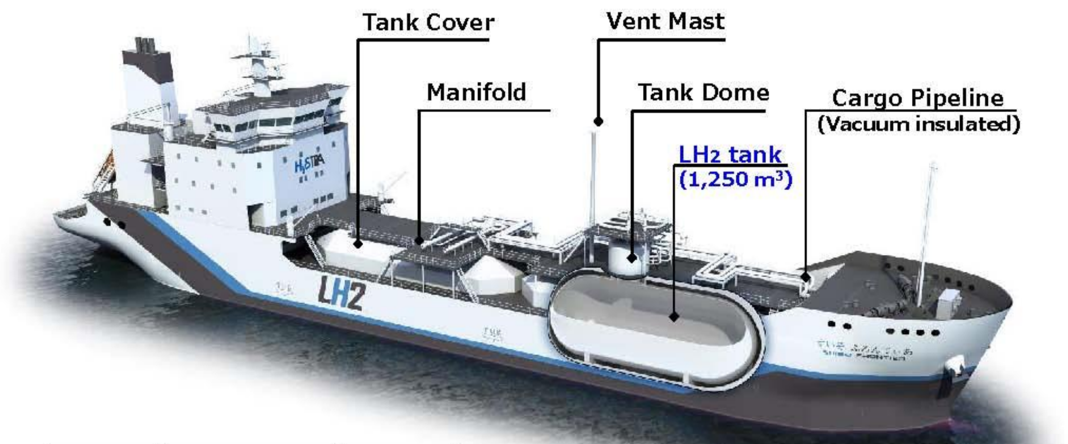
*NEDO : New Energy and Industrial Technology Development Organization
*METI: Ministry of Economy, Trade and Industry

Hydrogen Liquefier and Loading Base



Liquefied Hydrogen Carrier "Suiso Frontier"

Suiso: Hydrogen in Japanese



Length	116 m	Speed	13 knot
Width	19 m	Draft	4.5 m
Max crew	25 person	Propulsion	Diesel electric

© HySTRA

LH_2: Liquefied Hydrogen

Liquefied Hydrogen Carrier "Suiso Frontier"

Launch ceremony
at KHI Kobe Factory
(11 December 2019)

Cargo Tank Installation
at KHI Harima Works
(7 March 2020)

LH2 Receiving Terminal

LH_2: Liquefied Hydrogen

Development of Scaling Up on LH_2

LH_2: Liquefied Hydrogen

Pilot ship tank: 1,250m^3

X 32

Commercial ship tank: 40,000m^3

Pilot terminal tank: 2,500m^3

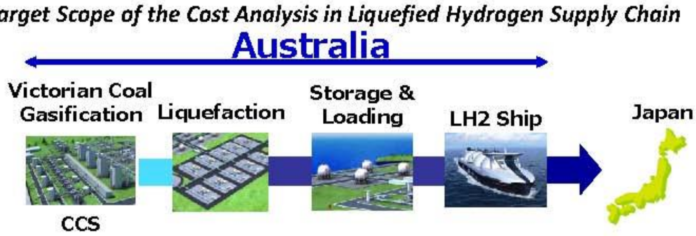
X 20

Commercial terminal tank: 50,000m^3

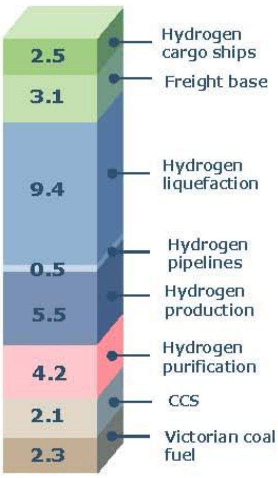
Interface equipment (ex: Loading arm) also under development

Estimation of hydrogen cost in 2030

Target Scope of the Cost Analysis in Liquefied Hydrogen Supply Chain



Hydrogen cost (CIF)@2030
29.7 yen/Nm^3

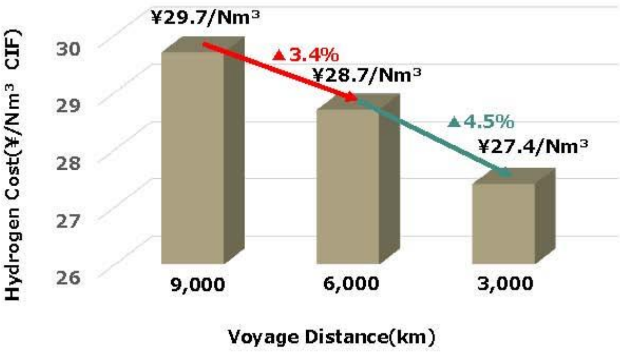


Precondition for Hydrogen Cost Calculation in 2030

Item	Unit	FS results
Victorian Coal Consumption	Mt / y	4.74
Victorian Coal Cost	AU$ / t	15
CCS Amount	Mt / y	4.39
CCS Cost	AU$ / t	15
Hydrogen Production	t / d	770
Hydrogen import in JPN	t / y	225,540

Item	Unit	Condition
Project period	year	30
Borrowing period	year	15
Years of depreciation	year	15
Tax	%	30
Investment and debt ratio	-	50 : 50
Borrowing rate	%/y	3

Analysis on Hydrogen Transport Costs by Voyage Distance



Voyage Distance(km)	9000km	6000km	3000km
Hydrogen Cost(¥/Nm3 CIF)	29.7	28.7	27.4

Possibility of Hydrogen Cost Reduction in the Further Future

	2020FY	2030FY	2040FY	2050FY
	Pilot demonstration	Commercial start (2 ships operated)	40 ships operated	80 ships operated
		770t/day H2 	15,400t/day H2 	30,800t/day H2 
¥/Nm³@CIF cost Hydrogen transport amont Power generation capacity※ ※Assuming an operation rate of 90%	Technology / social demonstration	¥30/Nm³ 225 K t/y 650 MW	¥24/Nm³ 4,500 K t/y 13,000 MW	¥18/Nm³ 9,000 K t/y 26,000 MW
Power generation cost		¥16/kWh	¥14/kWh	¥11/kWh
Share of power generation CO2 reduction forecast		0.5% 3,000 K t-CO2	10% 60,000 K t-CO2	20% 120,000 K t-CO2

Role and Effect of CO_2-free Hydrogen Chain

1 Stable Supply

- Hydrogen from fossil fuel linked with CCS will realize vast and affordable energy supply

  → Contribute energy security

2 Environmental

- No CO_2 emissions when used (only water is emitted)

  → "Ultimate clean energy"

3 Improvement of Industrial Competitiveness

- Wide use of hydrogen brings Industrial growth → Deployment of Infrastructure export
- Hydrogen production started from fossil fuel shifted to the renewables in the future → Sustainability

Thank you for listening

Kawasaki, working as one for the good of the planet

世界の人々の豊かな生活と地球環境の未来に貢献する

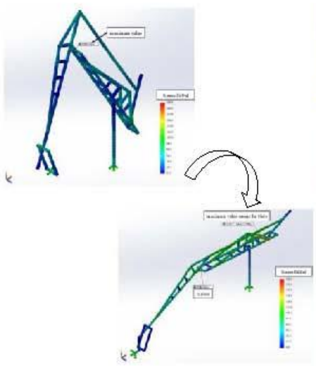
"Global Kawasaki"

Kawasaki Heavy Industries, Ltd.
Corporate Technology Division
https://global.kawasaki.com

Reference

Current situation -loading system-

- We applied flexible hoarse type for pilot project
- We did durability test under similar situation during operation



Simulation of maximum movable area

Subsidized by NEDO

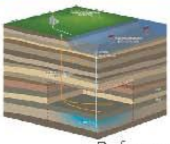
Hydrogen Gas Turbine CGS (Kobe Port Island)

Carbon Capture and Storage

- The Victorian Government and Australian Government promote CarbonNet Project
- Completed drilling an Offshore Appraisal Well (OAW) at the Pelican site in January 2020.
- Storage capacity 30Gt of CO2 under Bass Strait

Reference : METI

CCS Image



Reference : CO2CRC HP

Reference : Carbon Net HP