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

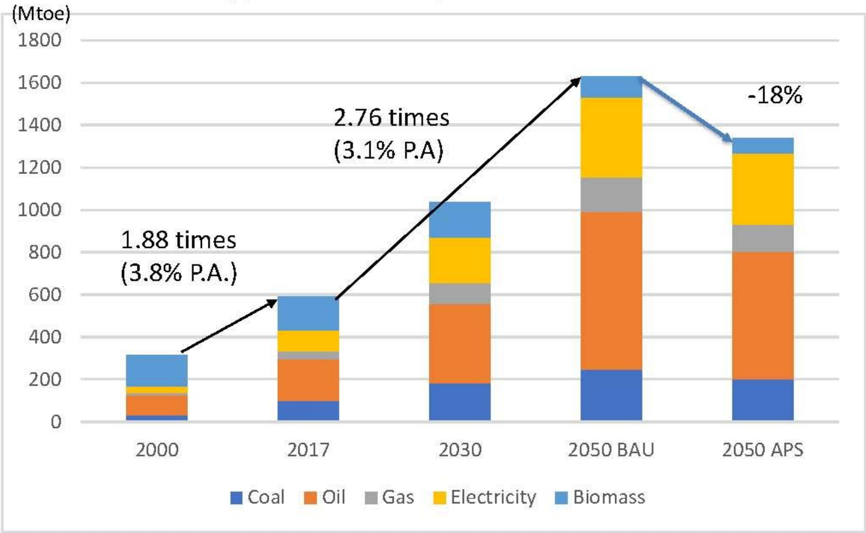
GDP per capita
1,980 thousand US$/person (constant 2010 price and US$) in 2017 increases to 9,950 thousand US$/person in 2050

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

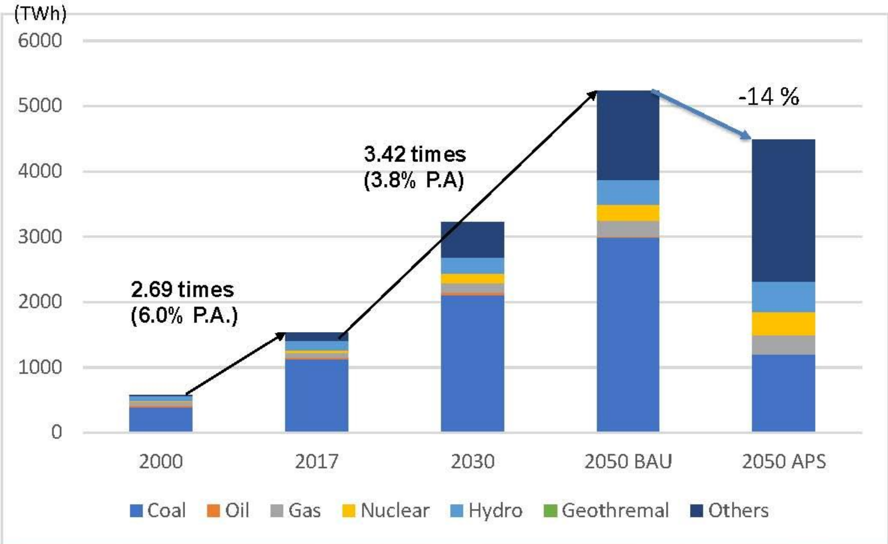
- Final Energy Consumption



Source: ERIA ESP WG Report 2019-20

EAS Energy Outlook Result of India

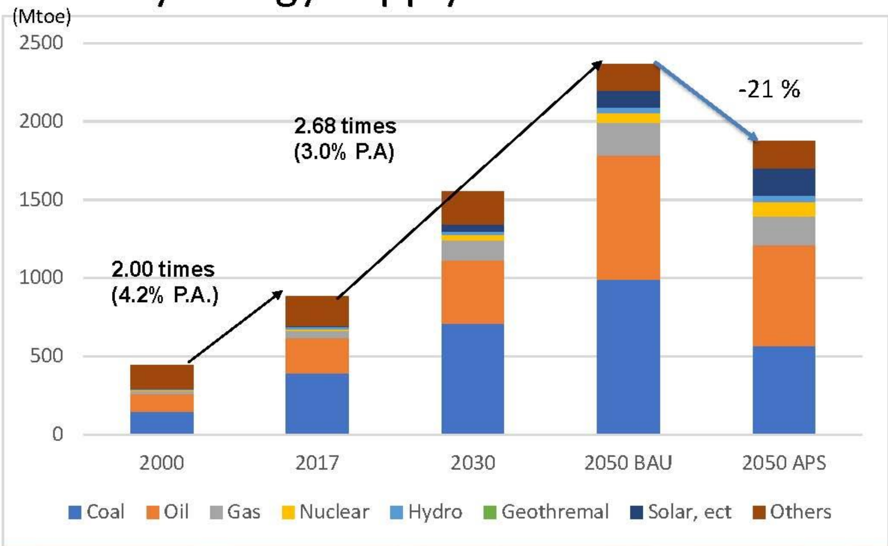
- Power Generation



Source: ERIA ESP WG Report 2019-20

EAS Energy Outlook Result of India

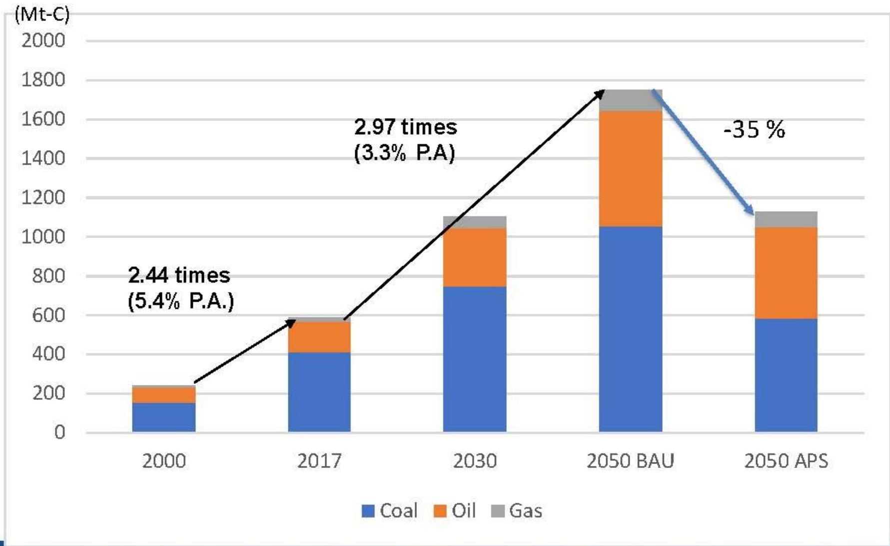
- Primary Energy Supply



Source: ERIA ESP WG Report 2019-20

EAS Energy Outlook Result of India

- CO2 Emissions

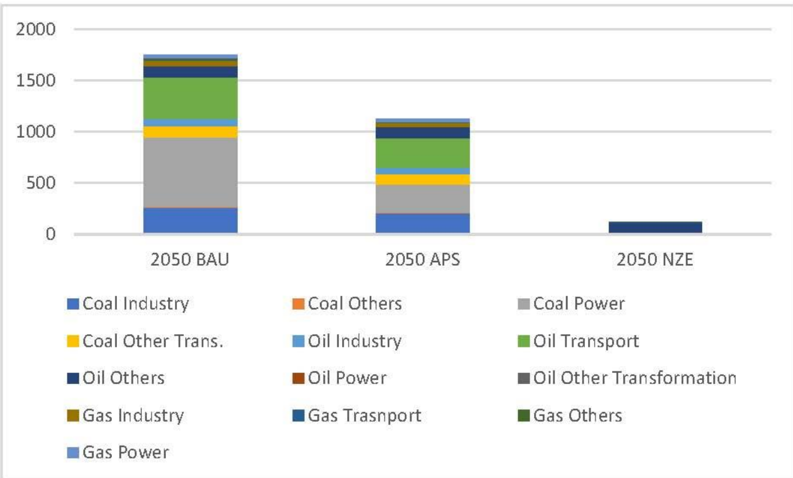


Source: ERIA ESP WG Report 2019-20

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)

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)

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

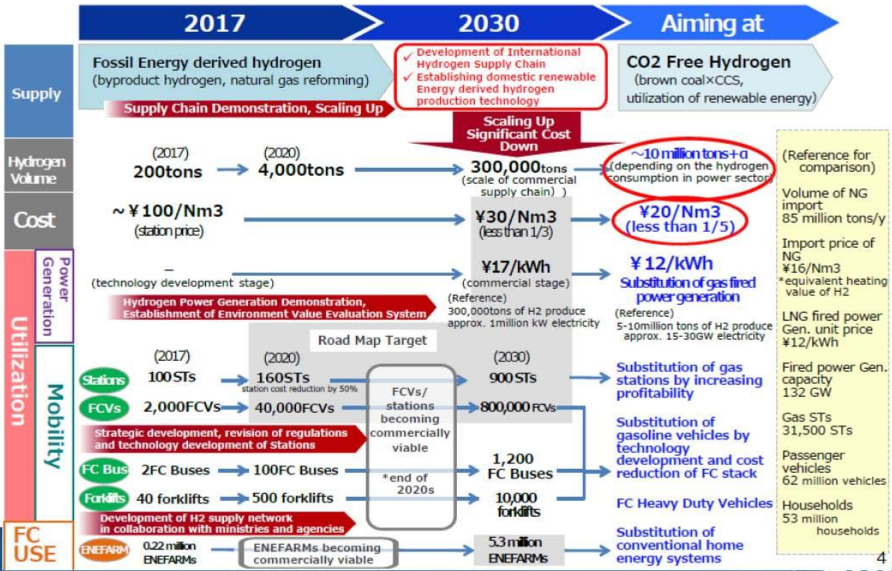
Hydrogen can be extracted from a wide range of substances including oil, natural gas, biofuels, sewage sludge, and can be produced from unlimited natural energy by the electrolysis of water.

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.

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"

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

IEEJ © 2021

ERIA/ARCI Workshop, June 2021

Hydrogen production and supply cost

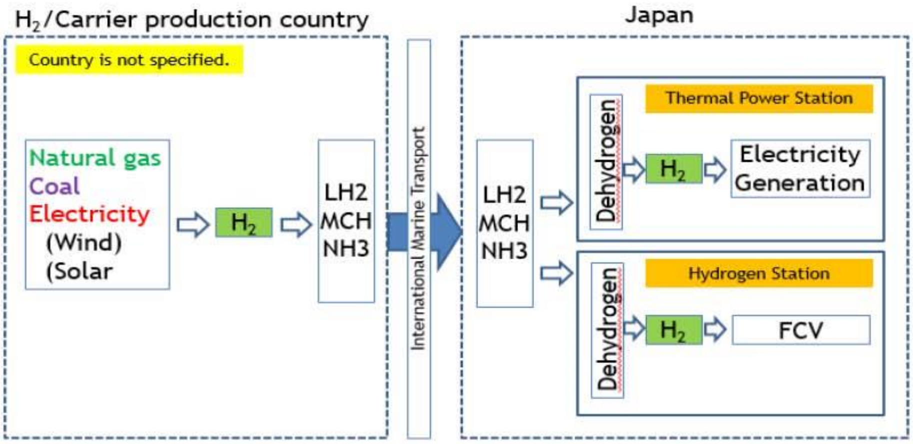
Ichiro KUTANI

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

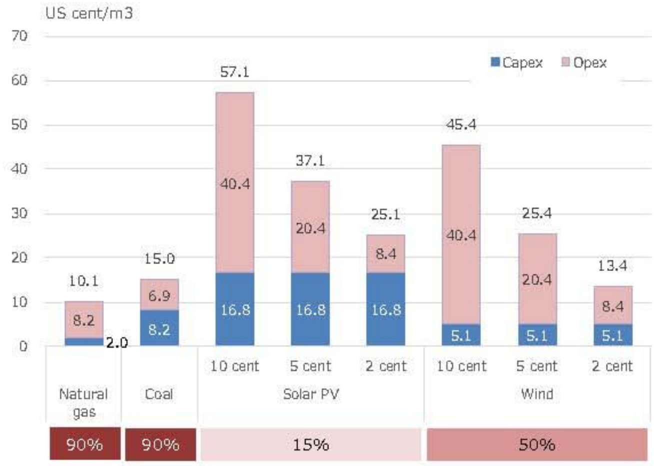
Source: ERIA (2020)

IEEJ © 2021

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 affect much.



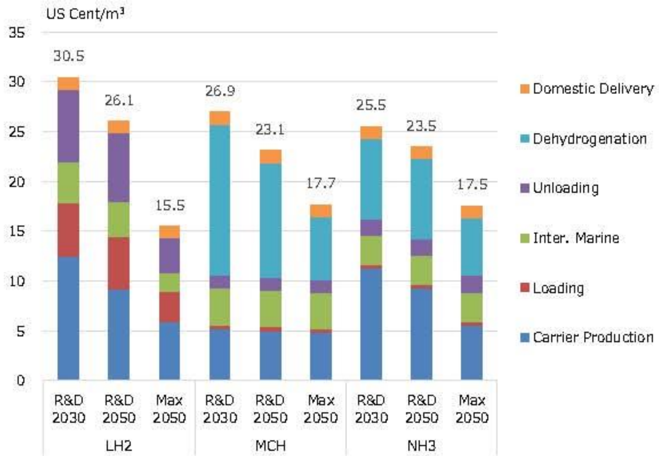
Capacity factor of a plant

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)

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

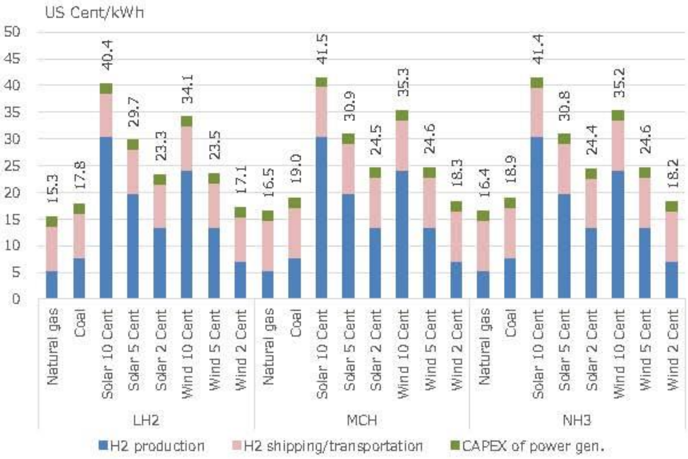
LN2 = liquified hydrogen
MCH = Methylcyclohexane
NH3 = ammonia
Source: ERIA (2020)

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.

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.

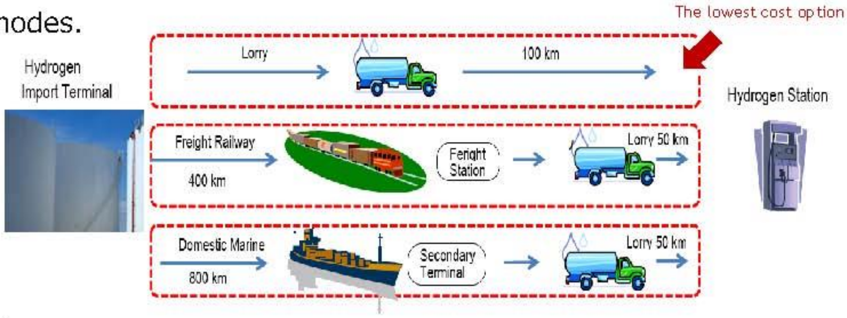
Demand = Max2050 scenario

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

4

H2 for vehicle 1

- 3 delivery modes.



- 3 demand sizes.

The lowest cost option

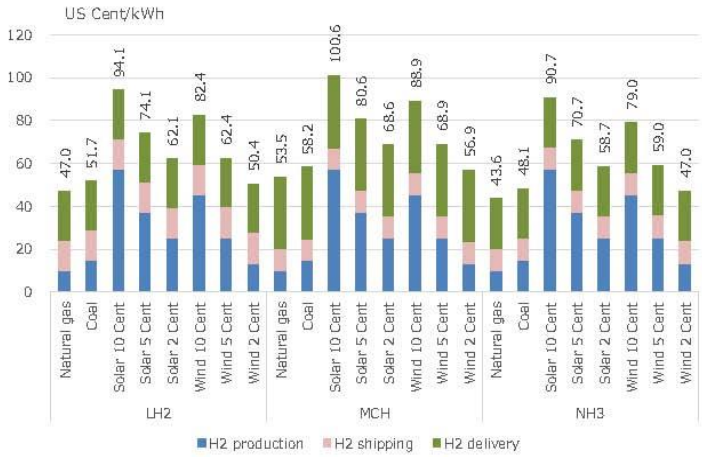
	Scenario		
	Small	Medium	Large
Hydrogen sales	300 Nm^3/h	Ave. 830 Nm^3/h Max. 1,200 Nm^3/h	Ave. 1,240 Nm^3/h Max. 2,400 Nm^3/h
(Gasoline sales equivalent)	(100 KL/month)	(200 KL/month)	(300 KL/month)
Number of visitors (Peak hour)	8 vehicles/h 2 dispensers	15 vehicles/h 3 dispensers	22 vehicles/h 4 dispensers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

5

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!

References;
NEDO, Analysis and Development on Hydrogen as an Energy Carrier/Economical Evaluation and Characteristic Analyses for Energy Carrier Systems (2014-2015)
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/

References

BGR 2020	BGR, BGR Energy Study 2019, July 2020
BP 2020	BP, Statistical review of world energy June 2020
ERIA 2018	ERIA, Demand and Supply Potential of Hydrogen Energy in East Asia
GCCSI 2020	GCCSI, Global Storage Resource Assessment -2019 update, June 2020
IEA 2020a	IEA, World Energy Balance database 2020
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

25 June 2021
Introductory Workshop on Hydrogen Potential Study of both Demand and Supply Sides

Hydrogen Demand Potential in EAS Region

Mitsuru MOTOKURA
Senior Coordinator,
Global Energy Group 1, Strategy Research Unit
The Institute of Energy Economics, Japan

Hydrogen Demand Potential Study

There are many uncertainties regarding the hydrogen supply chain due to varying promotion policies, utilisation technologies, transportation/distribution logistics, and costs.

Hydrogen Demand Potential Study consists assumptions and Scenarios.

In the Phase 1 Study, same scenarios were applied to all countries. (slide 10)
In the Phase 2 Study, countries were classified into four categories. (slide 11)

1

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)

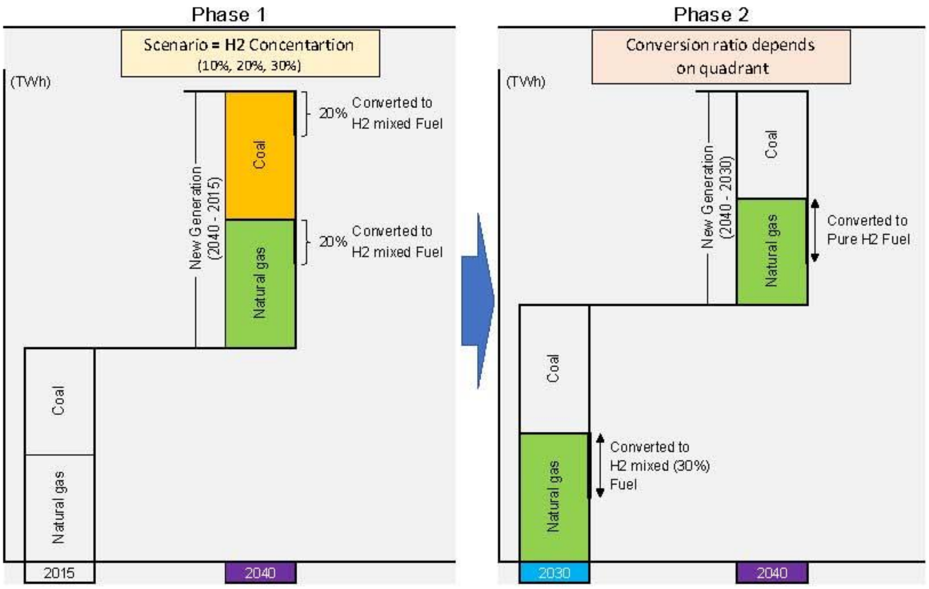
Not prevailed technology in 2040
- Utility scale FC
- FC-Heavy-Duty-Vehicle
- FC-Ship (Technically available, but international and domestic refueling infrastructures will only be partially established in 2040.)

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".

2

Scenarios (Phase 1 and Phase 2)

Sector: Electricity Generation

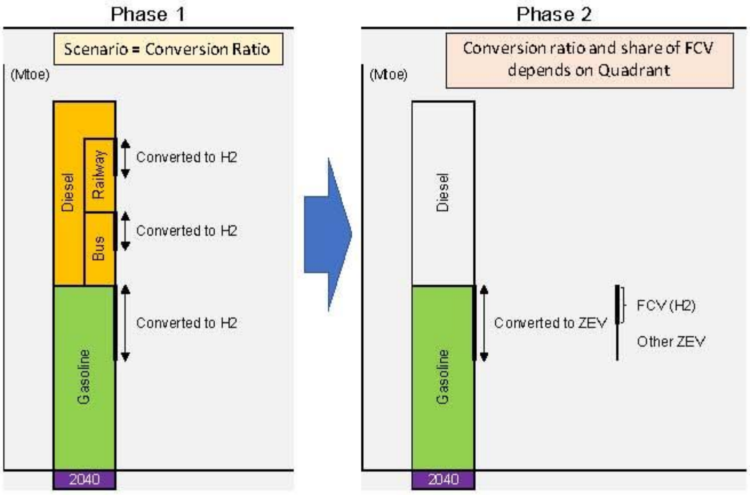


Note; Coal was excluded in the Phase 2 Study.

3

Scenarios (Phase 1 and Phase 2)

Sector: Transport

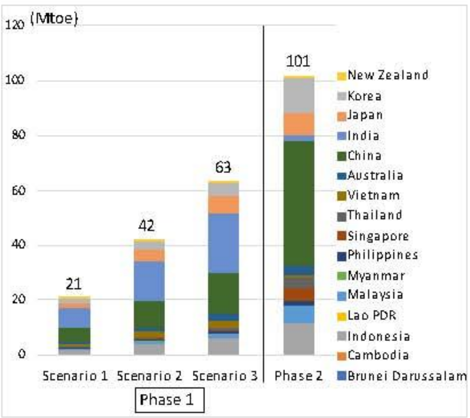


Note; Diesel was excluded in the Phase 2 Study.

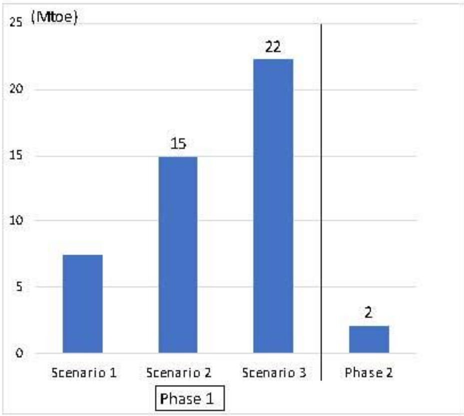
Hydrogen Demand Potential

Sector: Electricity Generation

EAS



India

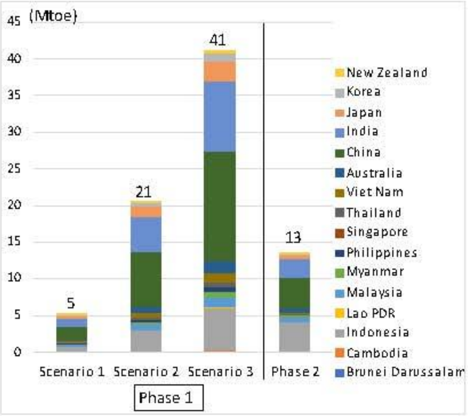


China will have the largest Potential in EAS region.
Compared to the Phase 1 Study, the Potential of India will decrease in the Phase 2 Study because Coal was excluded.

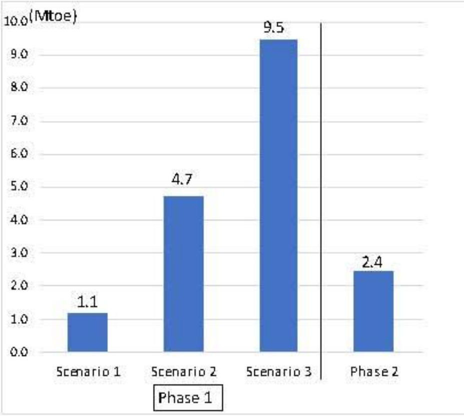
Hydrogen Demand Potential

Sector: Transport

EAS



India



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

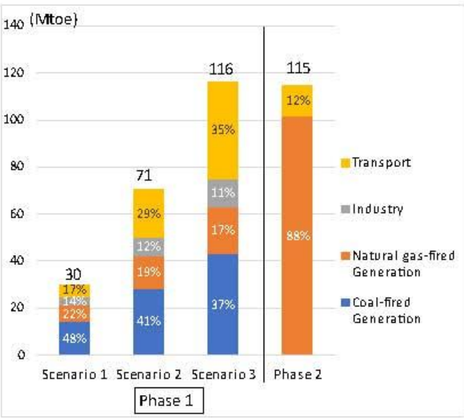
China and Indonesia will have the largest Potential in EAS region. India has the third largest Potential.

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

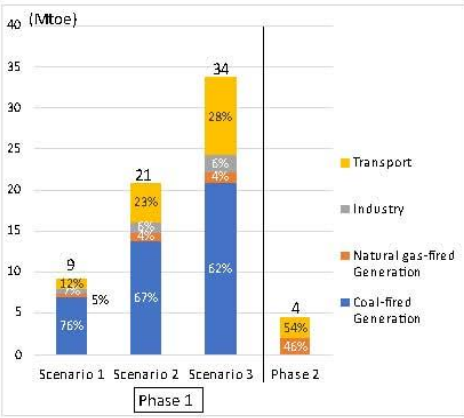
Hydrogen Demand Potential

Sector: Total

EAS



India



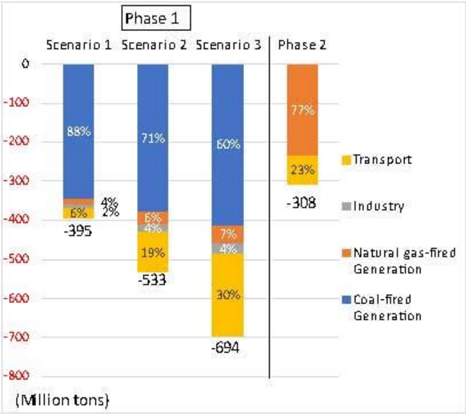
Note; Some corrections are included from the ERIA Phase 2 Report.

In the Phase 2 Study, Industry sector was excluded.

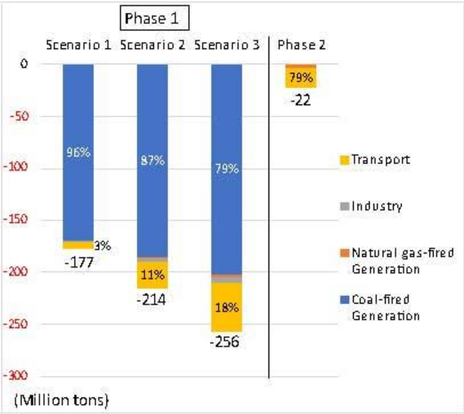
CO_2 Emission Reduction

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.

8

Appendix

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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	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%

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/m3 Net calorific value: 10,780 kJ/m3 = 2,575 kcal/m3 = 30,834 kcal/kg = 3,884 m3/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

Demand and Supply Potential of Hydrogen Energy in East Asia – Phase 2

Session 4: Introduction of Hydrogen Transport Costs and its Perspective (Liquid Organic Hydrogen Carrier)

June 21, 2021

Chiyoda Corporation

CONTENTS

I. **Liquid Organic Hydrogen Carrier (LOHC)**

II. **LOHC Transport Costs and its Perspective**

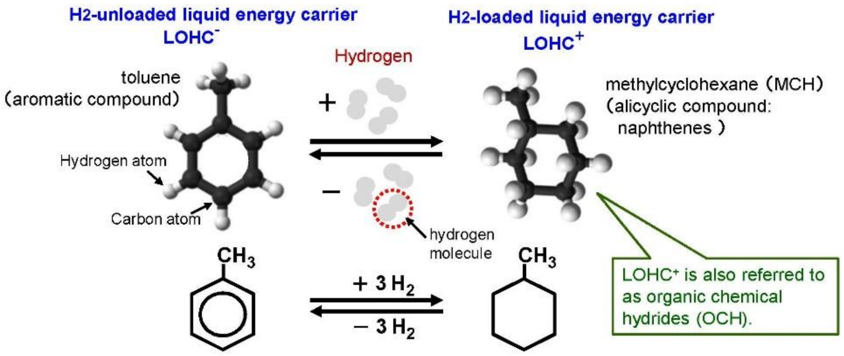
2

I. Liquid Organic Hydrogen Carrier (LOHC)

CHIYODA CORPORATION 3

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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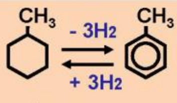
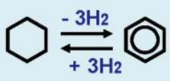
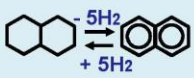
Liquid Organic Hydrogen Carrier (LOHC) : Several types

	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	 ΔH = 205 kJ/mol		 ΔH = 206 kJ/mol		 ΔH = 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-H_2/m^3)	47	−	56	−	65	−

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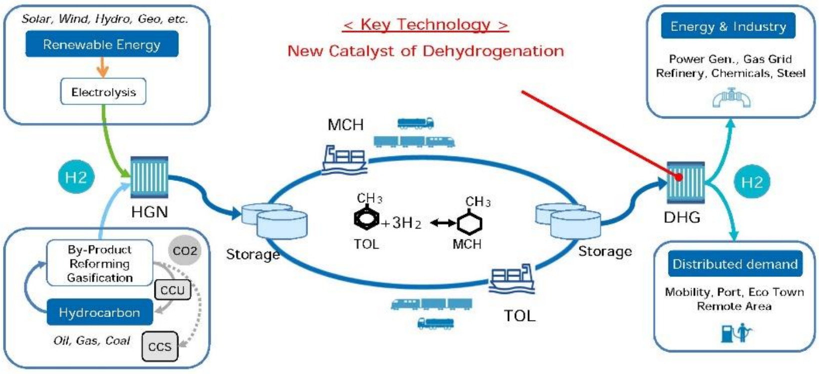
MCH Hydrogen Supply Chain Overview

- 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

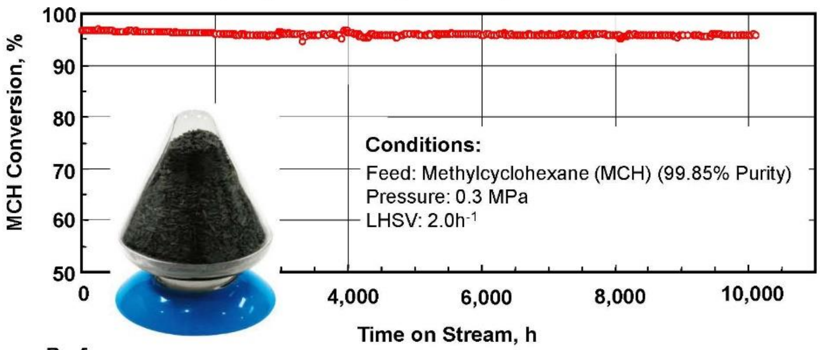
Long term storage & long distance transportation	Chemically stable, minor MCH (H_2) loss during long term storage and long distance transportation
Easy to handle	Liquid under ambient temperature and pressure Approximately 1/500 in volume
Use of existing oil infrastructure	Utilize existing infrastructure, 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

CHIYODA CORPORATION 7

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**

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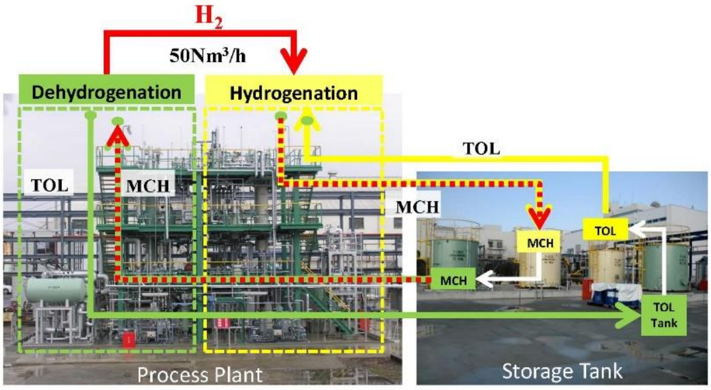
MCH Technology Development : Phase 2 (Pilot Test)

- 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



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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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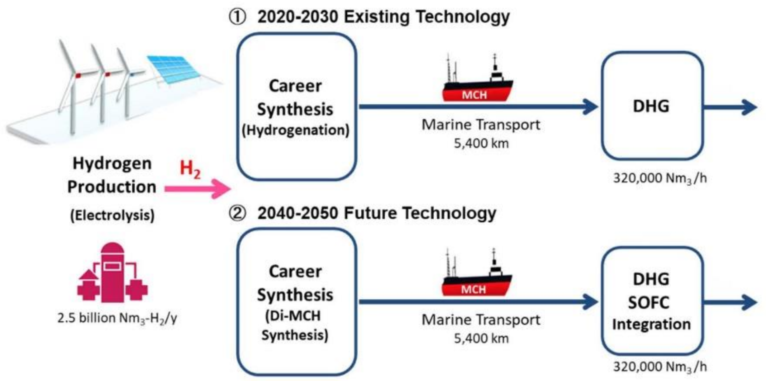
II. LOHC Transport Costs and its Perspective

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



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Model of Global Hydrogen Supply Chain : Future Technology

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

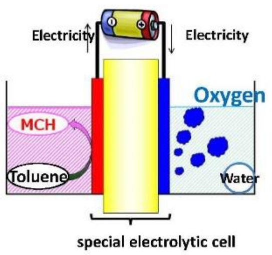
Future technologies:

- ✓ 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)

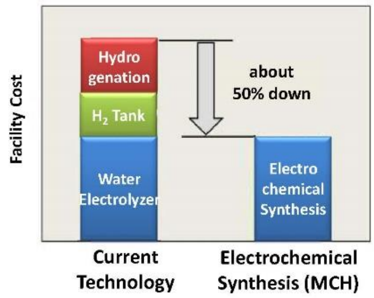
- MCH is produced directly from electricity, water and toluene through an integrated process of electrolysis and hydrogenation (MCH electrochemical synthesis technology).

MCH Electrochemical Synthesis Technology
(Electricity -> MCH)



** Laboratory scale test completed in 2019*

Facility Cost Reduction Potential



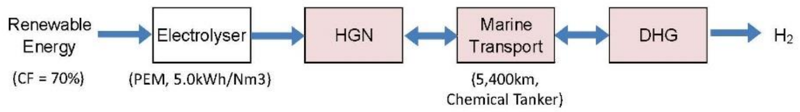
** In case of 6,000 Nm^3/h-H_2 (3 MW scale)*

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

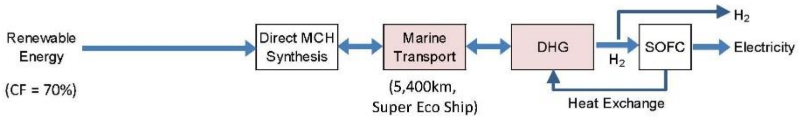
Model of Global Hydrogen Supply Chain : Key Assumptions

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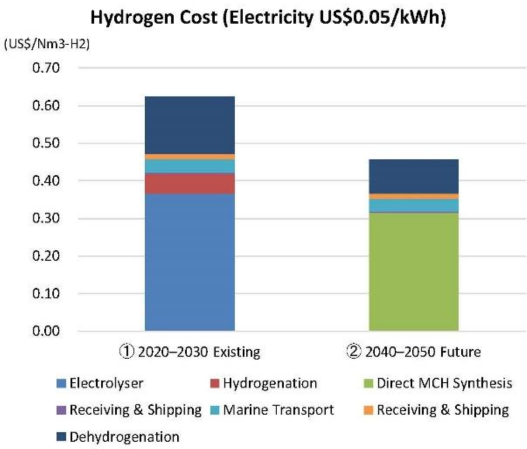
Global Hydrogen Supply Chain Cost (US$0.05/kWh)

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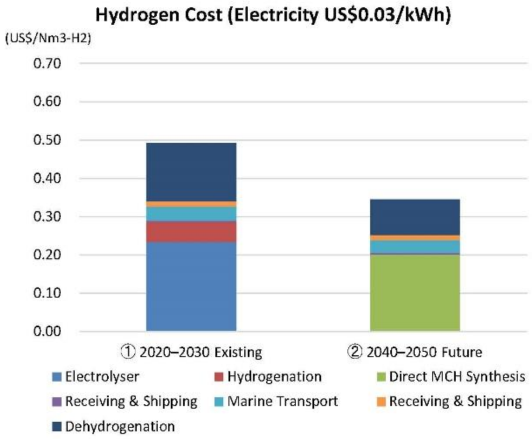
Global Hydrogen Supply Chain Cost (US$0.03/kWh)

- 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.



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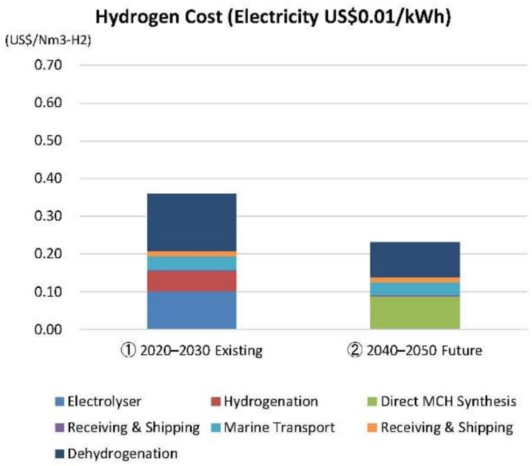
Global Hydrogen Supply Chain Cost (US$0.01/kWh)

- 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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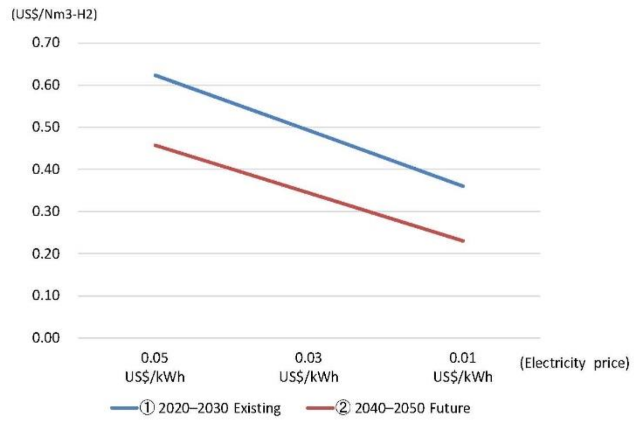
Global Hydrogen Supply Chain Cost : Summary

- 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.



CHIYODA CORPORATION

Thank You

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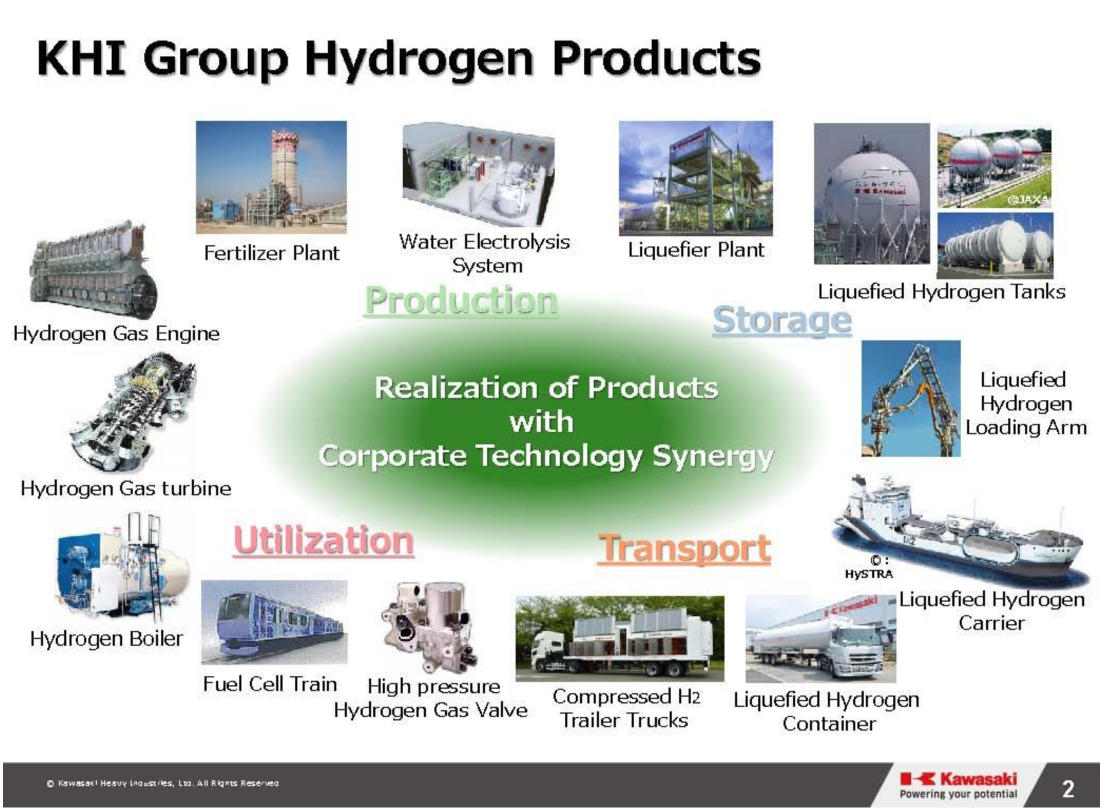
CHIYODA GROUP

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.

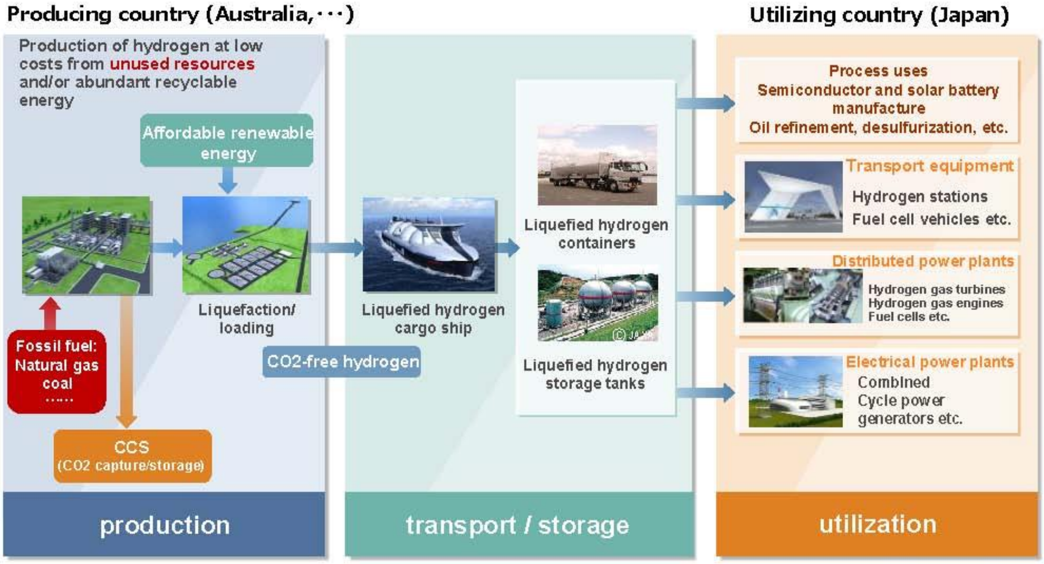
Kawasaki Heavy Industries contributes to achievement of decarbonization as the sole company in the world that owns the whole hydrogen supply chain technology for production, transportation, storage and utilization.

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



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

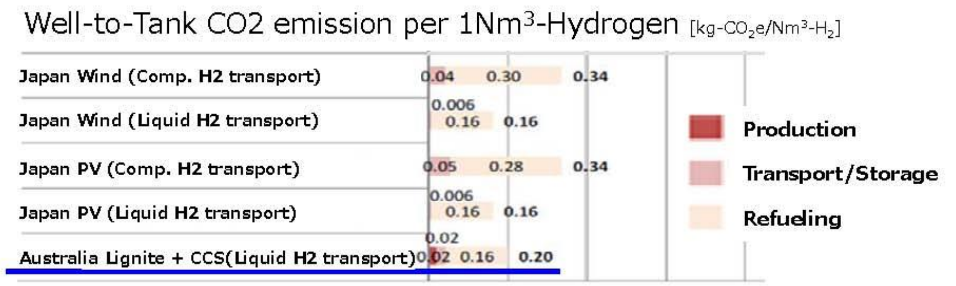
Liquefied hydrogen tanks (Tanegashima Rocket Base)


Largest liquefied hydrogen tanks in Japan (Kobe)

Commercial LH2 Carrier (Future)

LCA by Mizuho Information & Research Institute

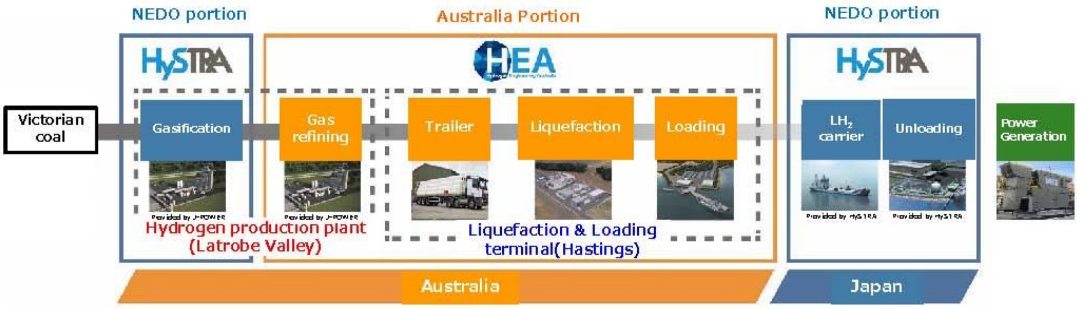
- Low CO2 emission equivalent to renewable oriented hydrogen



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)

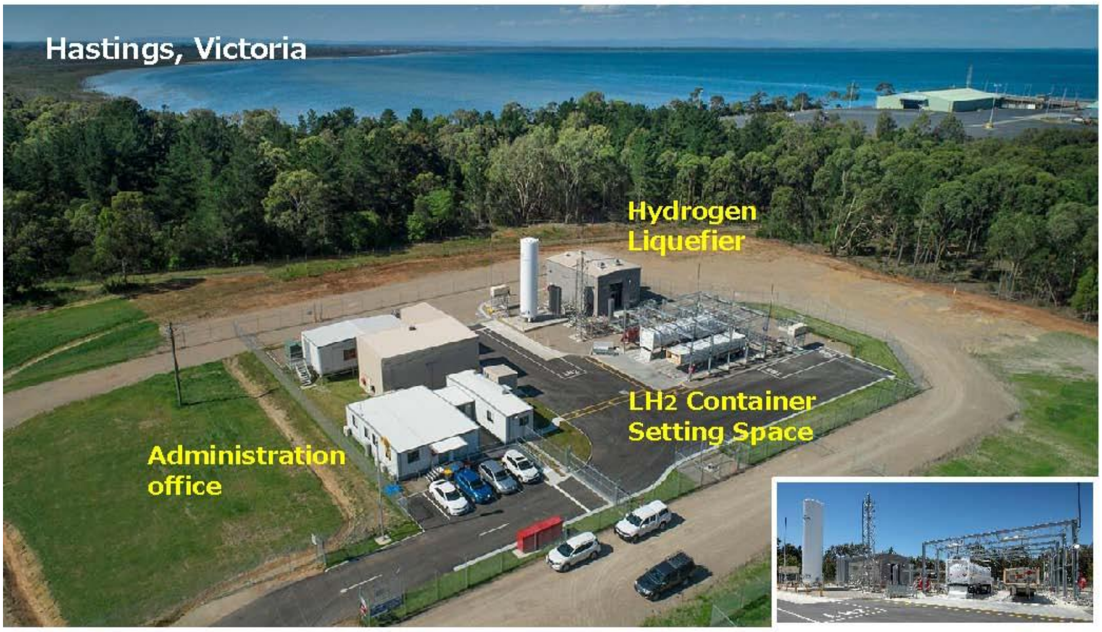
Kawasaki, Iwatani, J-Power, Shell Japan
Marubeni, ENEOS, KLINE
Supported by NEDO and METI

Hydrogen Engineering Australia (HEA)

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

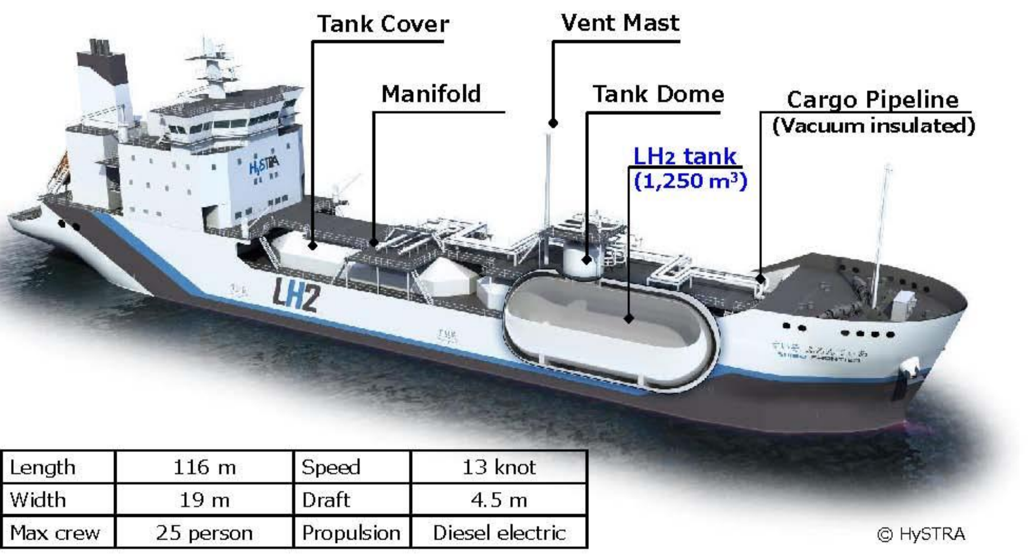
*NEDO : New Energy and Industrial Technology Development Organization
*METI: Ministry of Economy, Trade and Industry

Hydrogen Liquefier and Loading Base



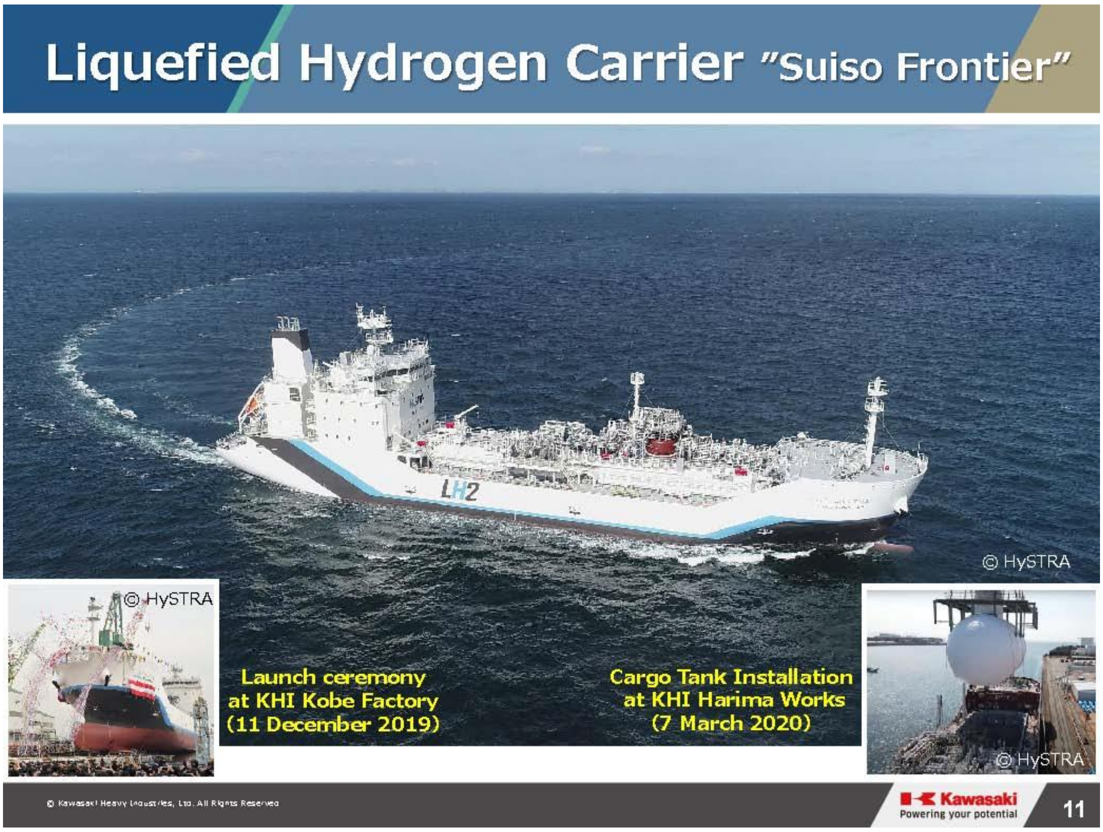
Liquefied Hydrogen Carrier "Suiso Frontier"

Suiso: Hydrogen in Japanese



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

LH_2: Liquefied Hydrogen


Liquefied Hydrogen Carrier "Suiso Frontier"
© HySTRA
© HySTRA
Launch ceremony
at KHI Kobe Factory
(11 December 2019)
Cargo Tank Installation
at KHI Harima Works
(7 March 2020)
© HySTRA
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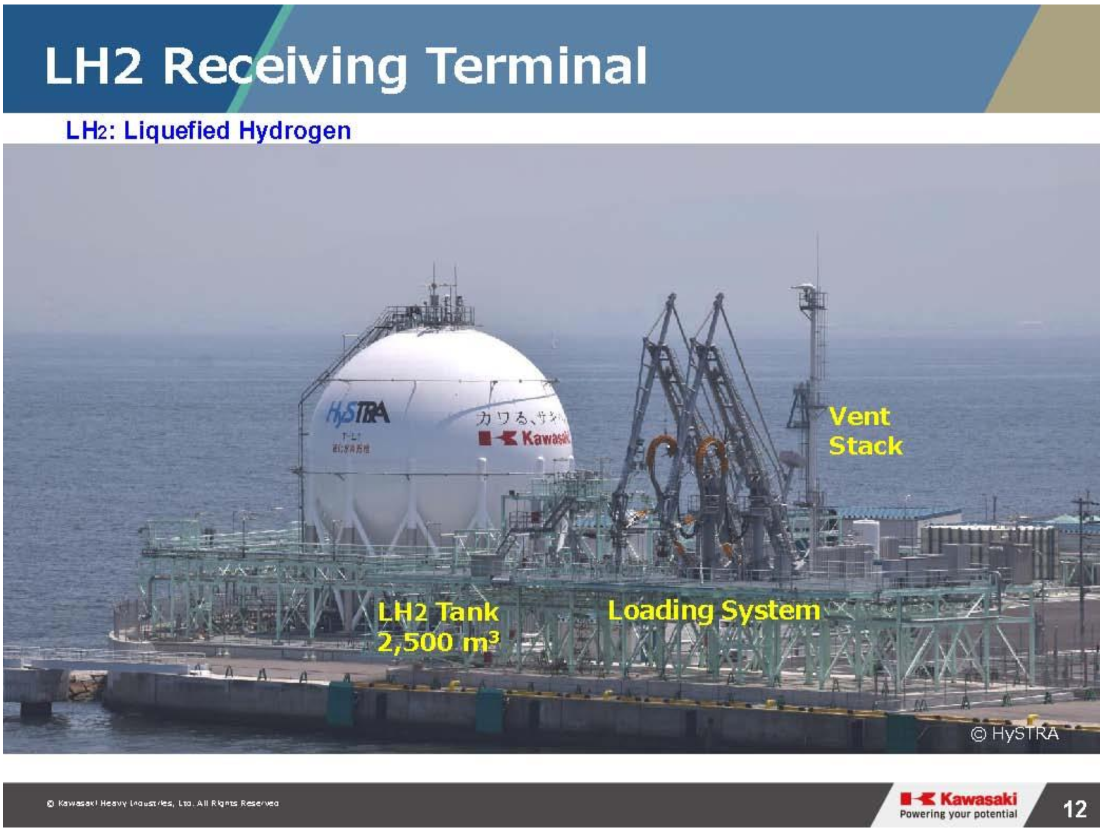
Powering your potential
11


LH2 Receiving Terminal
LH2: Liquefied Hydrogen
Vent
Stack
LH2 Tank
2,500 m³
Loading System
© HySTRA
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Powering your potential
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Development of Scaling Up on LH_2

LH_2: Liquefied Hydrogen

Pilot ship tank: 1,250m³

X 32

Commercial ship tank: 40,000m³

Pilot terminal tank: 2,500m³

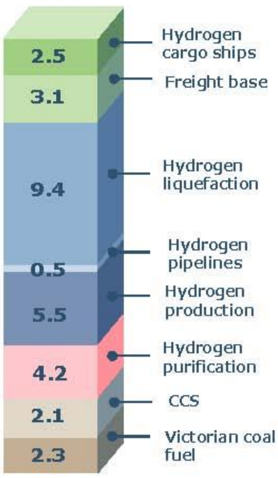
X 20

Commercial terminal tank: 50,000m³

Interface equipment (ex: Loading arm) also under development

Estimation of hydrogen cost in 2030

Hydrogen cost (CIF)@2030
29.7 yen/Nm³



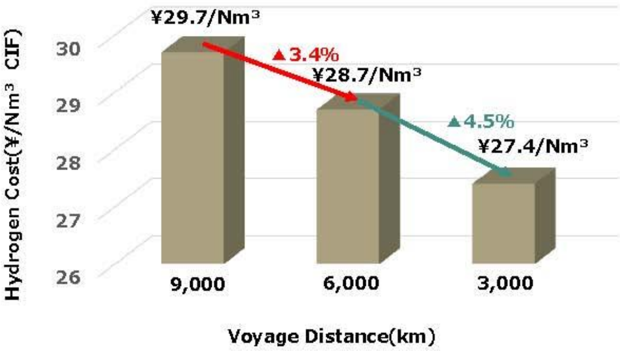
Target Scope of the Cost Analysis in Liquefied Hydrogen Supply Chain

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

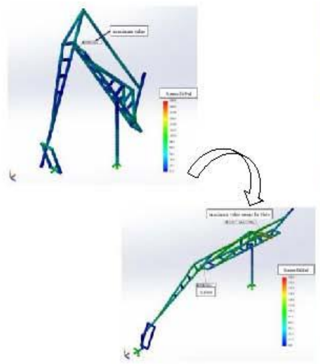
"Global Kawasaki"

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

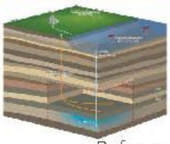
Subsidized by NEDO

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

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

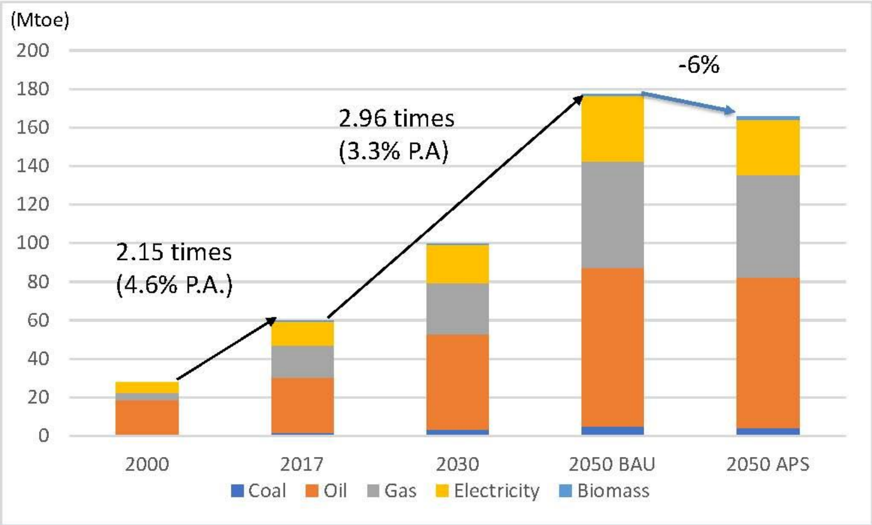
Crude Oil Price (nominal price)
Increase to about 250 US$/bbl in 2050 due to future tight balance between demand and supply

ERIA

Source: ERIA ESP WG Report 2019-20 3

EAS Energy Outlook Result of Malaysia

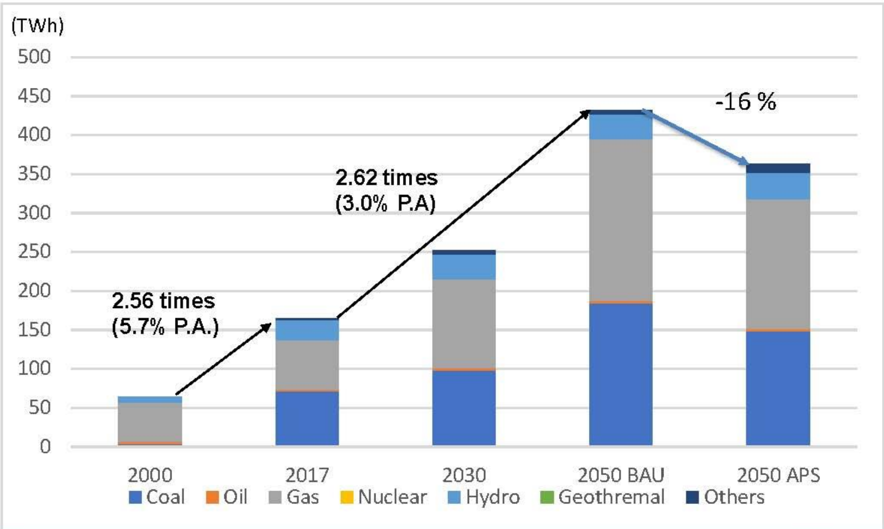
- Final Energy Consumption



Source: ERIA ESP WG Report 2019-20

EAS Energy Outlook Result of Malaysia

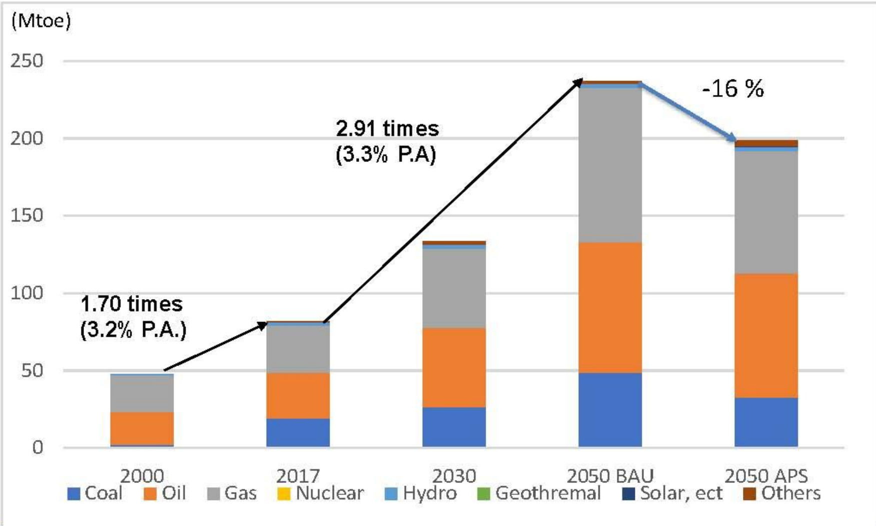
- Power Generation



Source: ERIA ESP WG Report 2019-20

EAS Energy Outlook Result of Malaysia

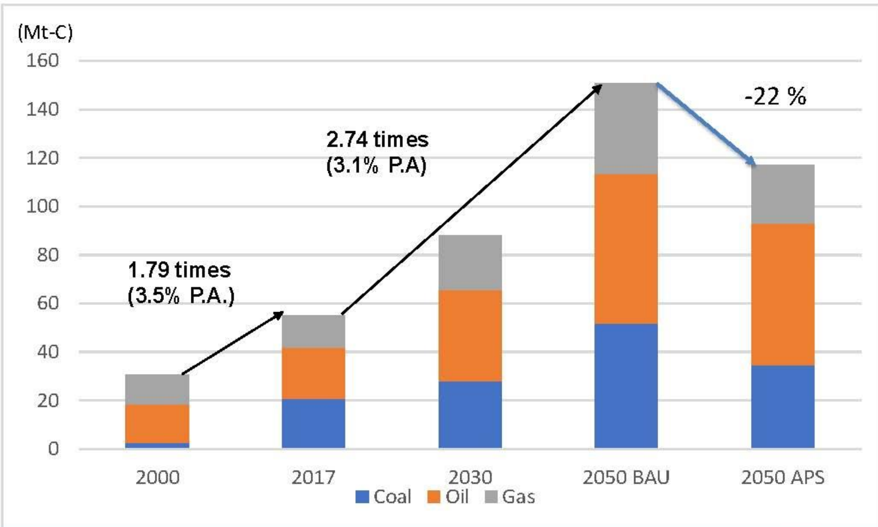
- Primary Energy Supply



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)

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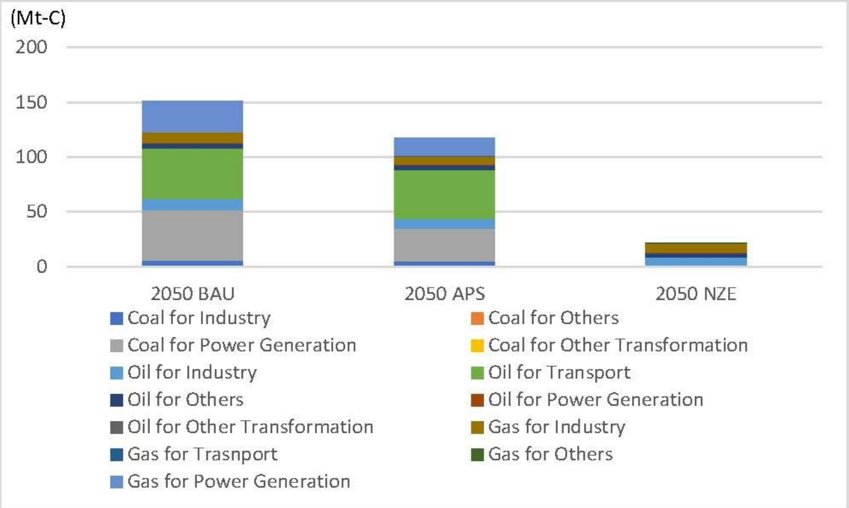
Net Zero Emission of Malaysia



Hydrogen: Gas Power and Oil for transport

Ammonia: Coal for Power

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.

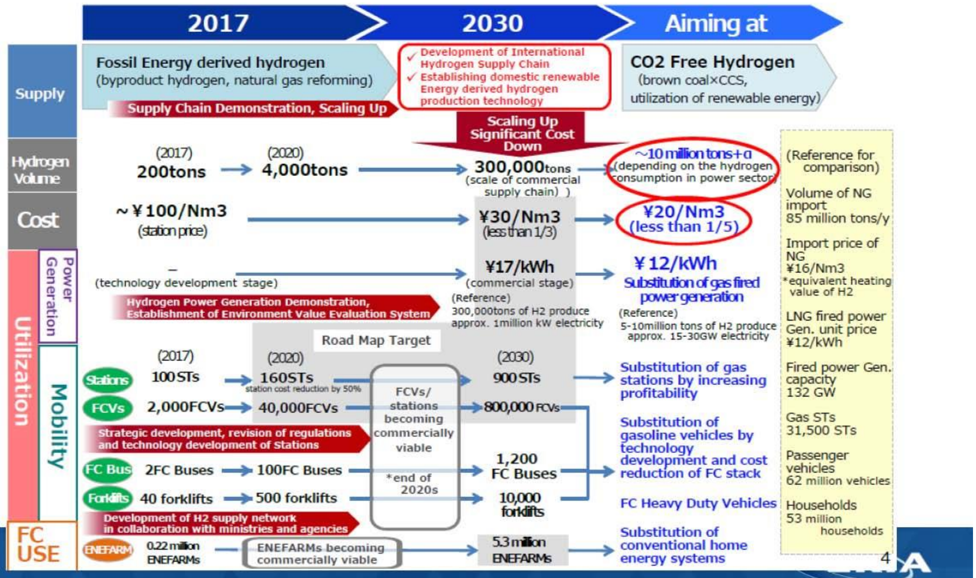
3. STORAGE AND TRANSPORTATION

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

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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

ERIA

Thank you for your attention!!

ERIA

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

IEEJ © 2021

ERIA/ARCI Workshop, July 2021

IEE JAPAN

Hydrogen production and supply cost

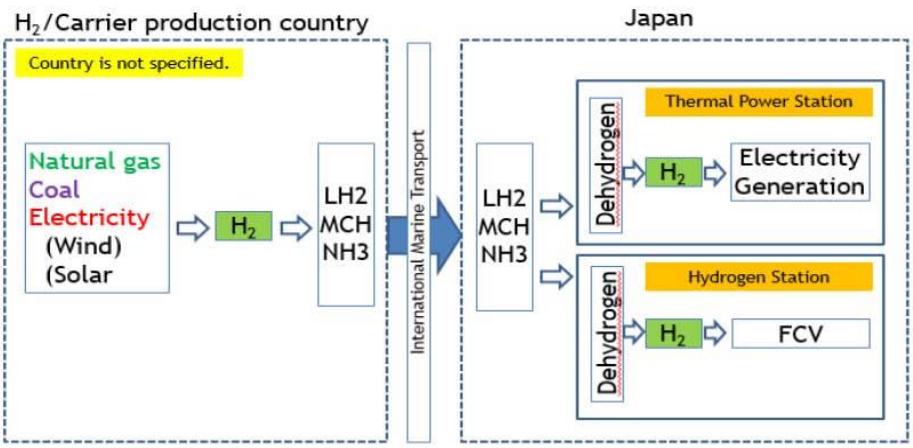
Ichiro KUTANI

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

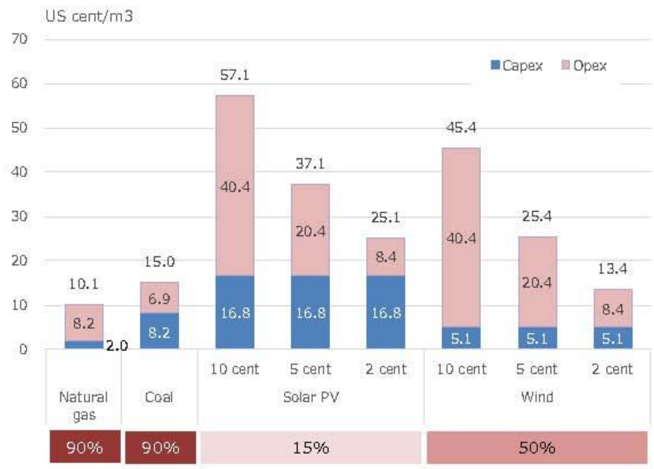
Source: ERIA (2020)

IEEJ © 2021

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.



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)

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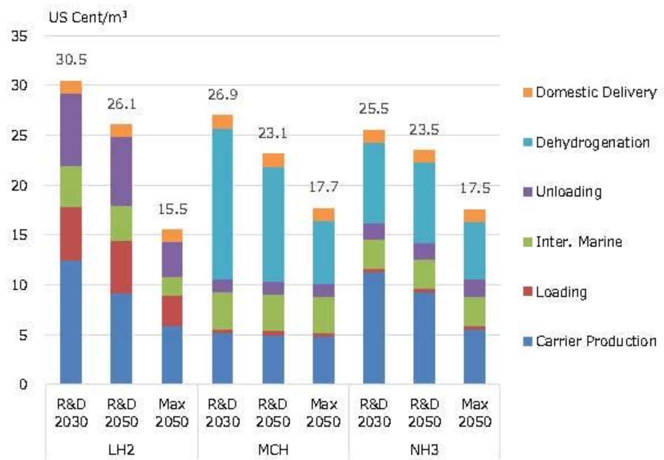
2

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.

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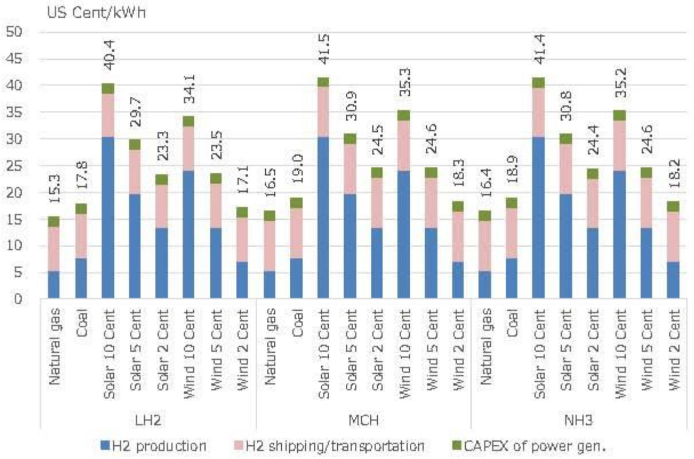
3

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.

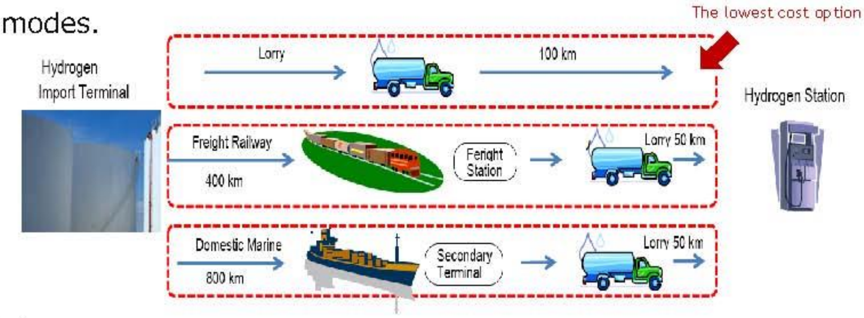
Demand = Max2050 scenario

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

4

H2 for vehicle 1

- 3 delivery modes.



- 3 demand sizes.

The lowest cost option

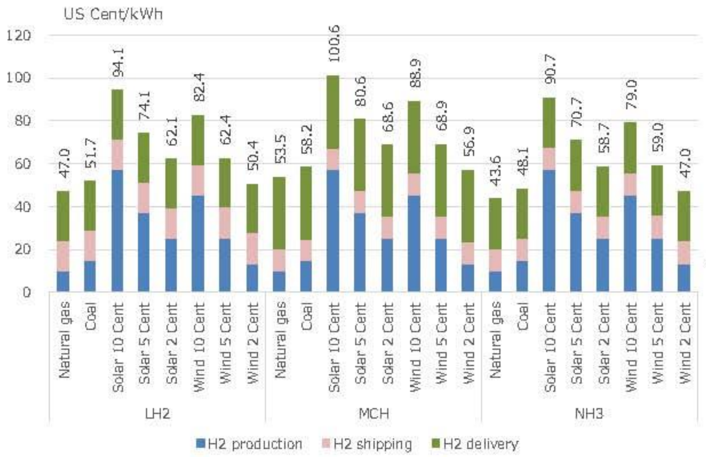
	Scenario		
	Small	Medium	Large
Hydrogen sales	300 Nm³/h	Ave. 830 Nm³/h Max. 1,200 Nm³/h	Ave. 1,240 Nm³/h Max. 2,400 Nm³/h
(Gasoline sales equivalent)	(100 KL/month)	(200 KL/month)	(300 KL/month)
Number of visitors (Peak hour)	8 vehicles/h 2 dispensers	15 vehicles/h 3 dispensers	22 vehicles/h 4 dispensers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

5

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!

References;
NEDO, Analysis and Development on Hydrogen as an Energy Carrier/Economical Evaluation and Characteristic Analyses for Energy Carrier Systems (2014-2015)
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/

References

BGR 2020	BGR, BGR Energy Study 2019, July 2020
BP 2020	BP, Statistical review of world energy June 2020
ERIA 2018	ERIA, Demand and Supply Potential of Hydrogen Energy in East Asia
GCCSI 2020	GCCSI, Global Storage Resource Assessment -2019 update, June 2020
IEA 2020a	IEA, World Energy Balance database 2020
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

29 July 2021
Introductory Workshop on Hydrogen Potential Study of both Demand and Supply Sides

Hydrogen Demand Potential in EAS Region

Mitsuru MOTOKURA
Senior Coordinator,
Global Energy Group 1, Strategy Research Unit
The Institute of Energy Economics, Japan

Hydrogen Demand Potential Study

There are many uncertainties regarding the hydrogen supply chain due to varying promotion policies, utilisation technologies, transportation/distribution logistics, and costs.

↓

Hydrogen Demand Potential Study consists of assumptions and Scenarios.

In the Phase 1 Study, same scenarios were applied to all countries. (slide 10)
In the Phase 2 Study, countries were classified into four categories. (slide 11)

1

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".

2

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%

3

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%

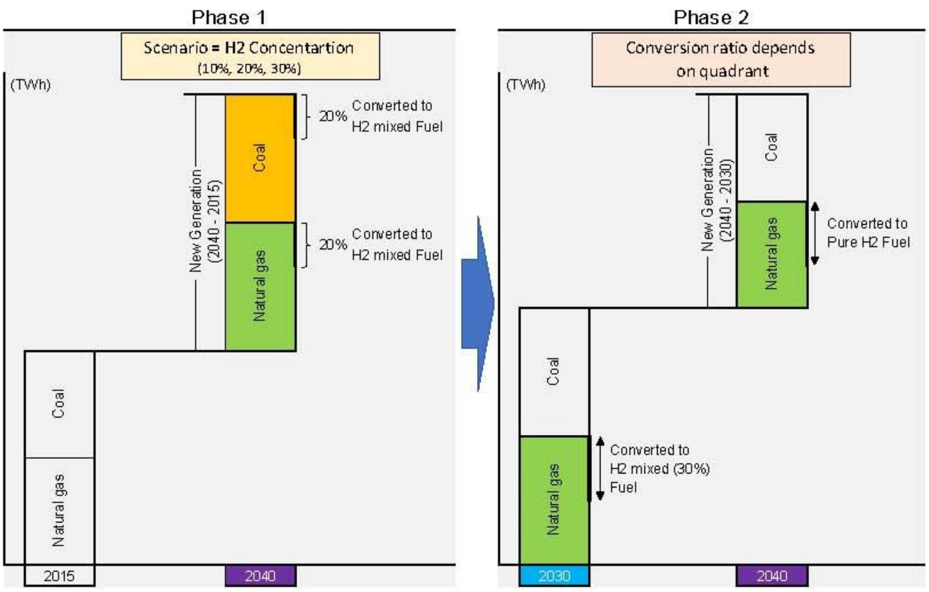
Major Differences of Scenarios (Phases 1 and 2)

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

10

Comparison of Scenarios (Phase 1 & 2)

Sector: Electricity Generation

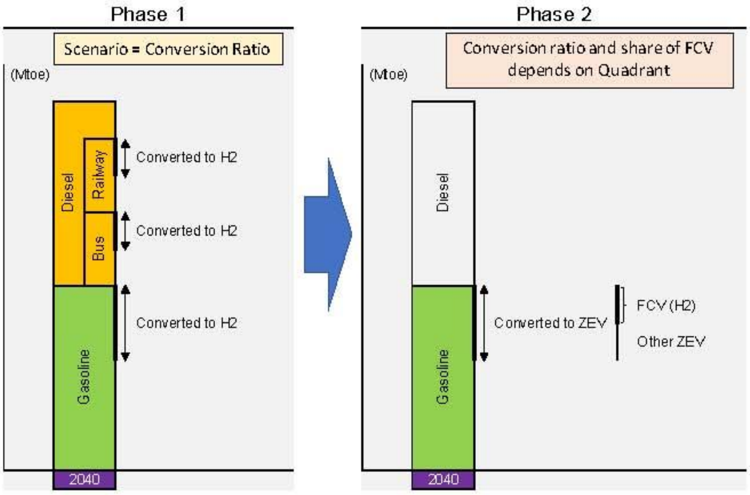


Note; Coal was excluded in the Phase 2 Study.

11

Comparison of Scenarios (Phase 1 & 2)

Sector: Transport

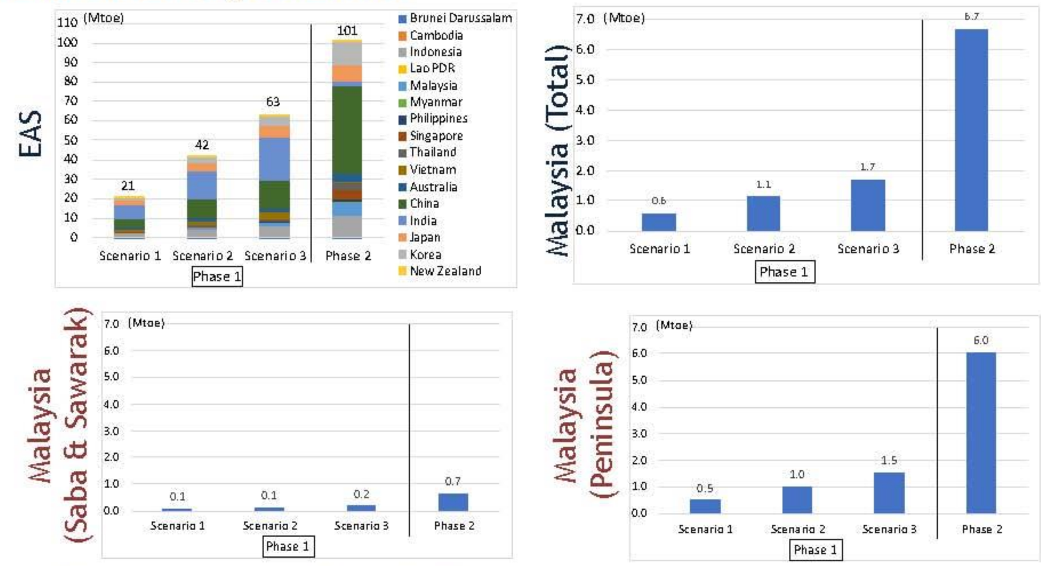


Note; Diesel was excluded in the Phase 2 Study.

12

Hydrogen Demand Potential

Sector: Electricity Generation

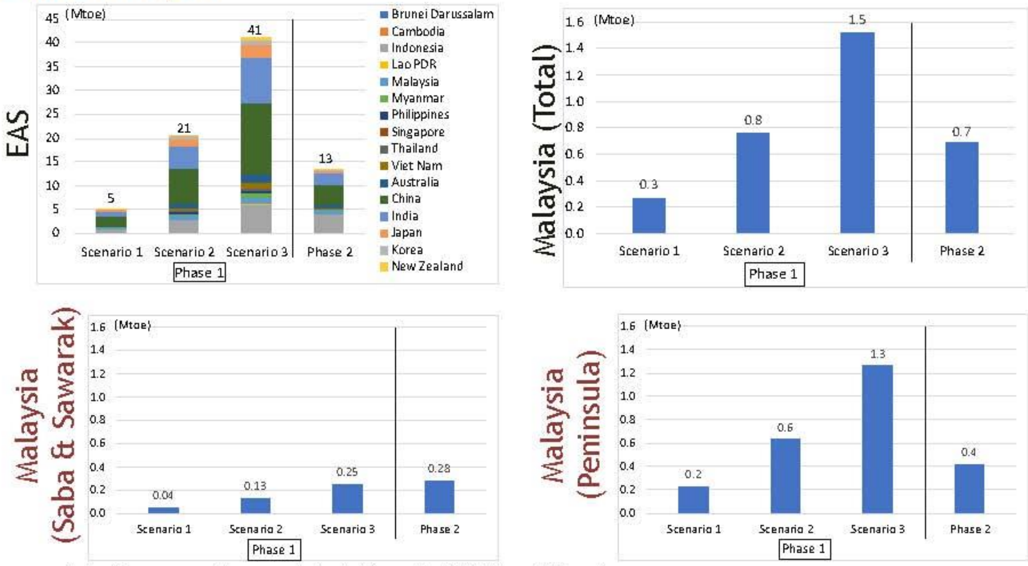


China will have the largest Potential in EAS region.
Compared to the Phase 1 Study, the Potential of Malaysia will increase in the Phase 2 Study because the scenario of Natural gas generation conversion was aggressive.

13

Hydrogen Demand Potential

Sector: Transport

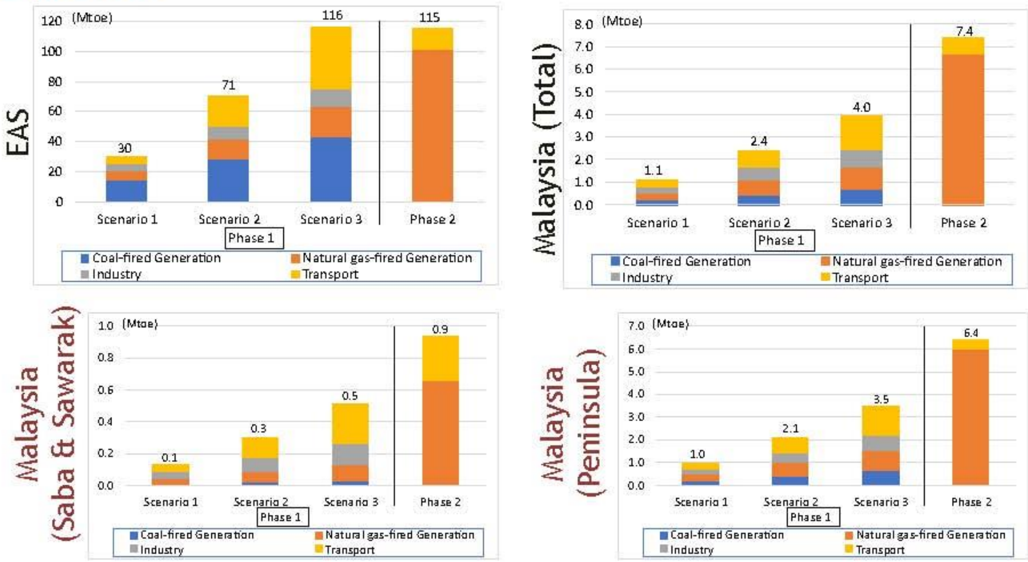


Note; Some corrections are included from the ERIA Phase 2 Report.

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

Hydrogen Demand Potential

Sector: Total

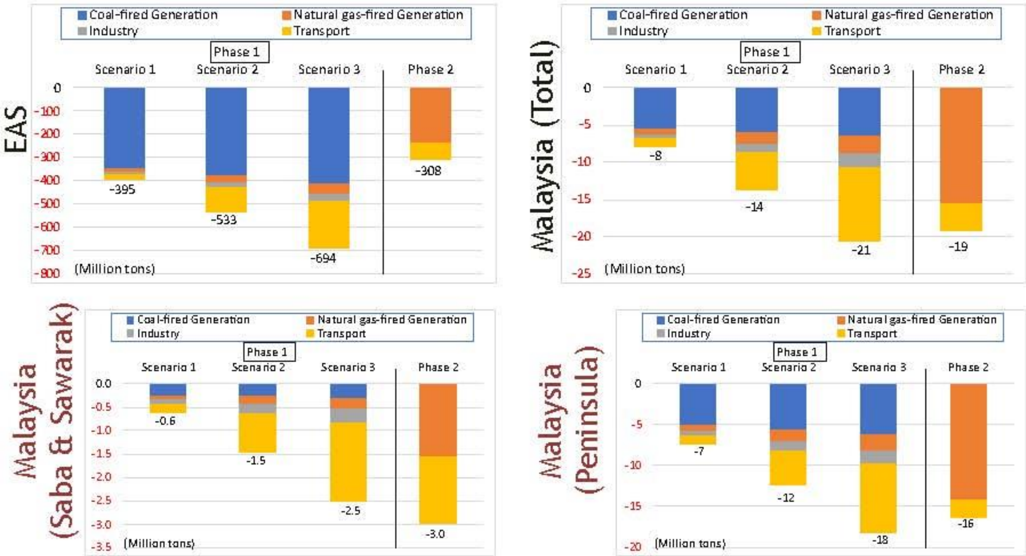


Note; Some corrections are included from the ERIA Phase 2 Report.

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

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.

Appendix

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!

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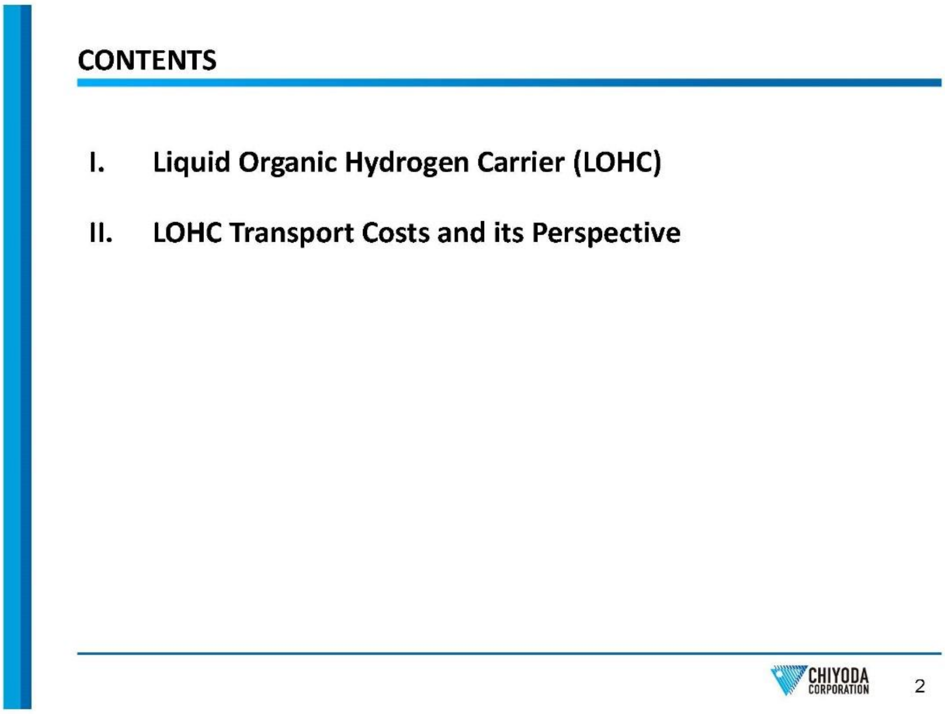
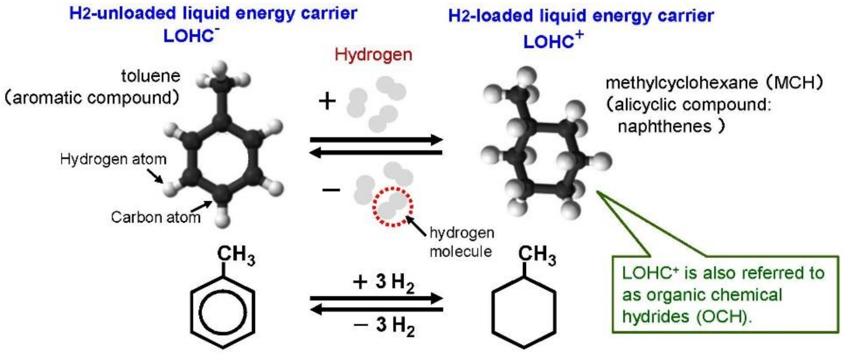
4. Session 4: Introduction of Hydrogen Transport Costs (Liquefied Hydrogen) by Chiyoda Corporation



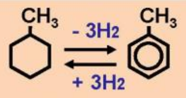
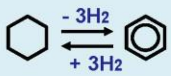
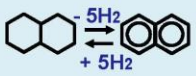
I. Liquid Organic Hydrogen Carrier (LOHC)

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.



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	 $-3H_2$ / $+3H_2$ ⊿H = 205 kJ/mol		 $-3H_2$ / $+3H_2$ ⊿H = 206 kJ/mol		 $-5H_2$ / $+5H_2$ ⊿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-H_2/m^3)	47	—	56	—	65	—

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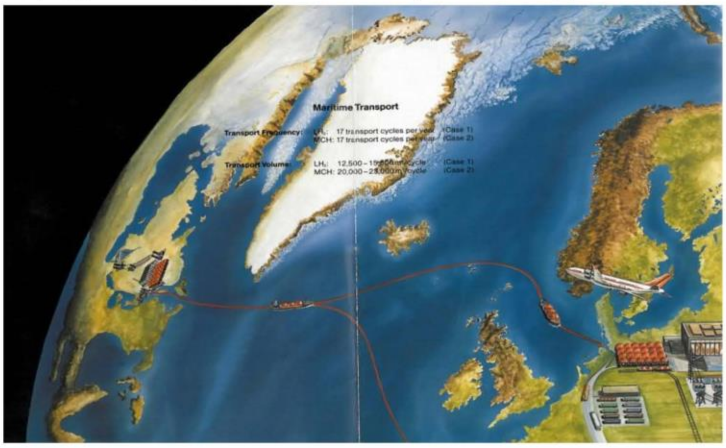
Liquid Organic Hydrogen Carrier (LOHC) : EQHHPP

- 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

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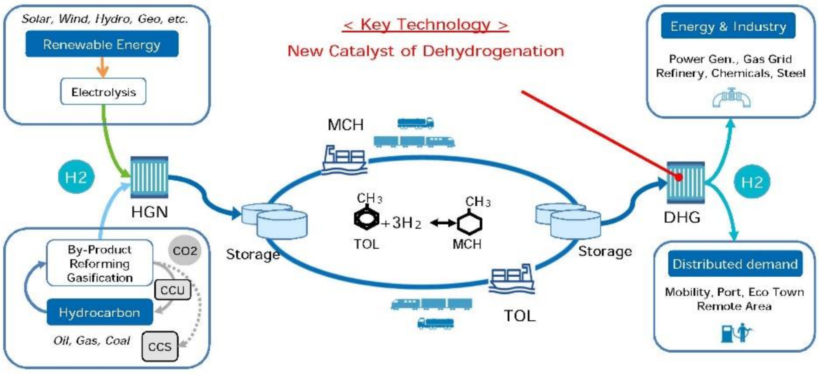
MCH Hydrogen Supply Chain Overview

- 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

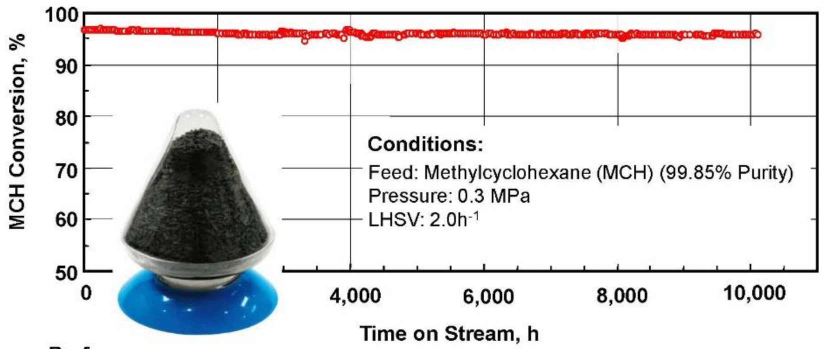
Long term storage & long distance transportation	Chemically stable, minor MCH (H_2) loss during long term storage and long distance transportation
Easy to handle	Liquid under ambient temperature and pressure Approximately 1/500 in volume
Use of existing oil infrastructure	Utilize existing infrastructure, 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

CHIYODA CORPORATION 8

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

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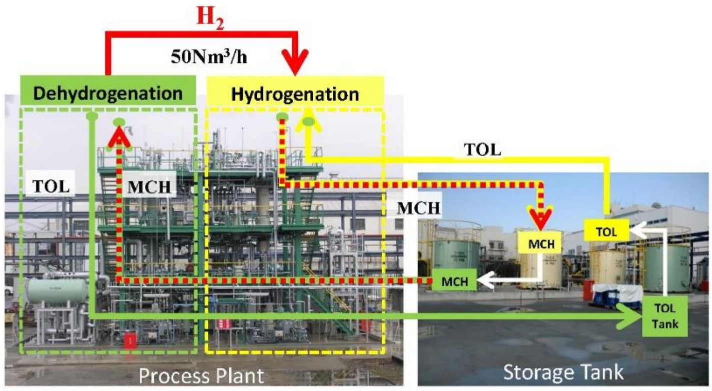
MCH Technology Development : Phase 2 (Pilot Test)

- 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



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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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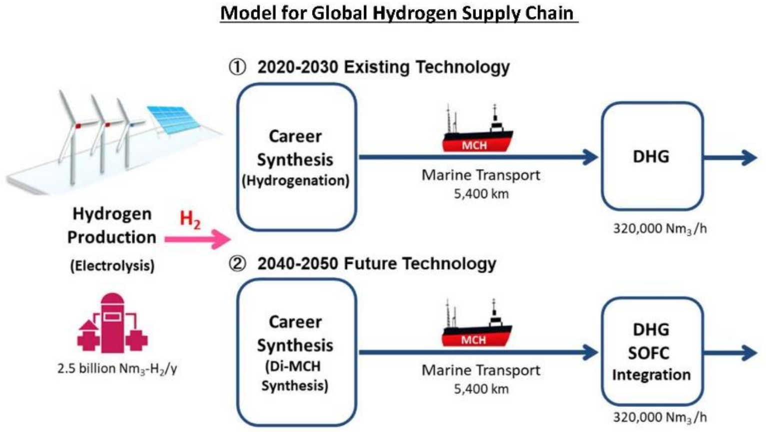
II. LOHC Transport Costs and its Perspective

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 of Global Hydrogen Supply Chain : Future Technology

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

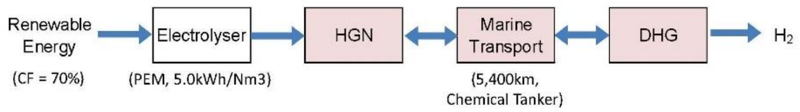
Future technologies:

- ✓ 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

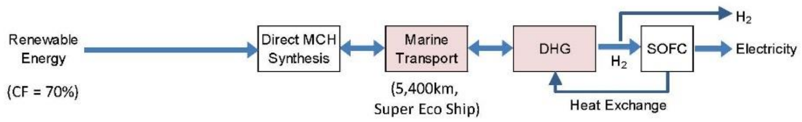
Model of Global Hydrogen Supply Chain : Key Assumptions

- 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



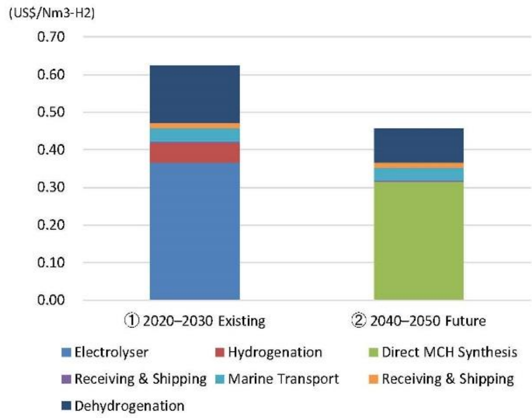
2. 2040 – 2050 Future Technology



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

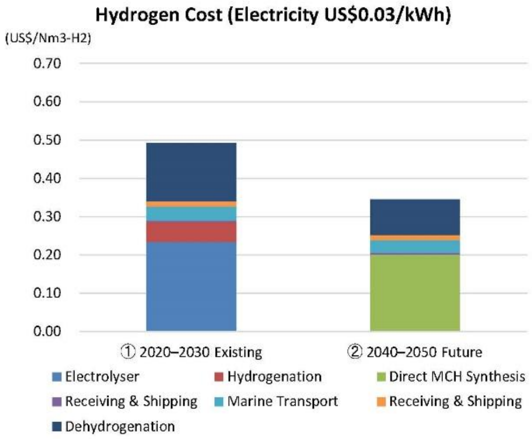
- At the electricity price of US$0.05/kWh, the hydrogen price in 2040–2050 is estimated to be reduced by around 25%, compared to US$0.62/Nm3 in 2020–2030.

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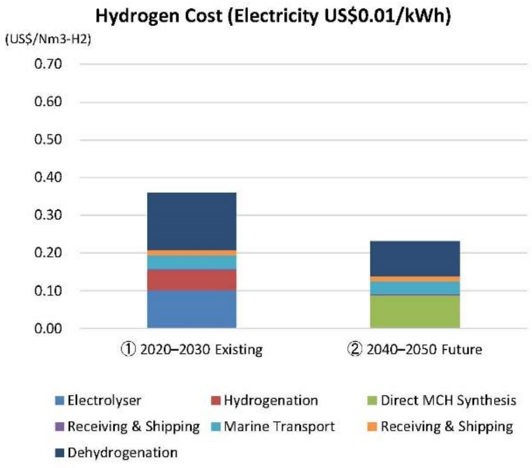
Global Hydrogen Supply Chain Cost (US$0.01/kWh)

- 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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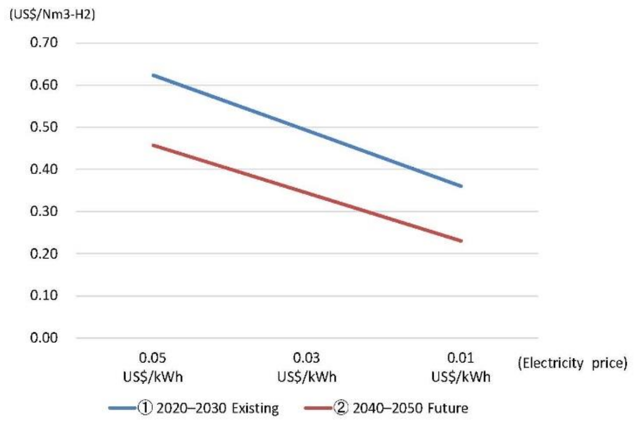
Global Hydrogen Supply Chain Cost : Summary

- 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.



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Thank You

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CHIYODA GROUP

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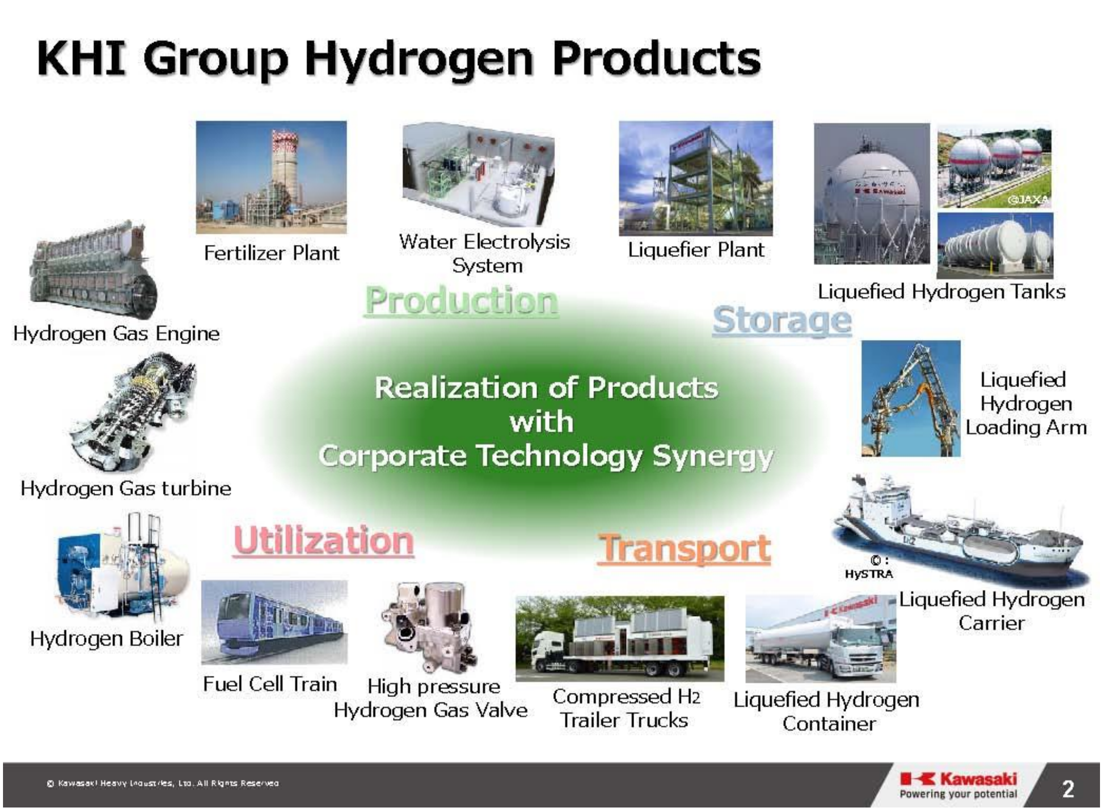
5. **Session 5: Introduction of Hydrogen Transport Costs (Liquefied Hydrogen) by Kawasaki Heavy Industries**



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.

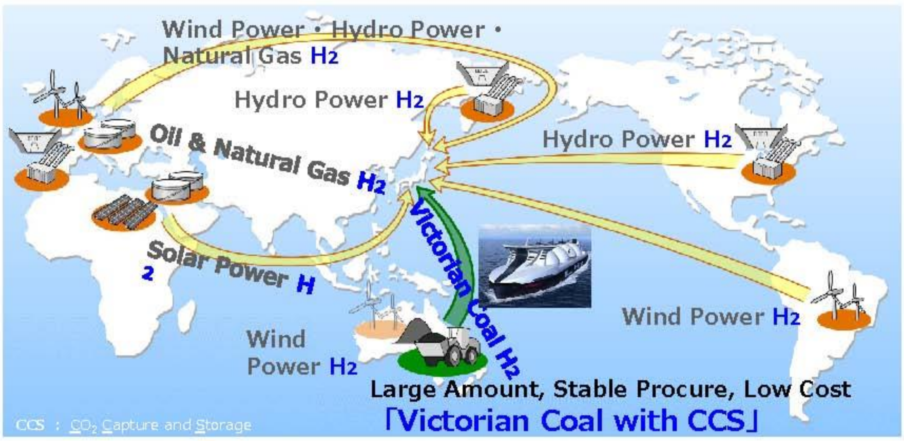
With extremely wide range of industries involved in hydrogen supply chain and demand field, hydrogen is highlighted worldwide due to creating a virtuous cycle for environment and economy.

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.

Kawasaki Powering your potential 3

CO_2-Free Hydrogen Resources in the World

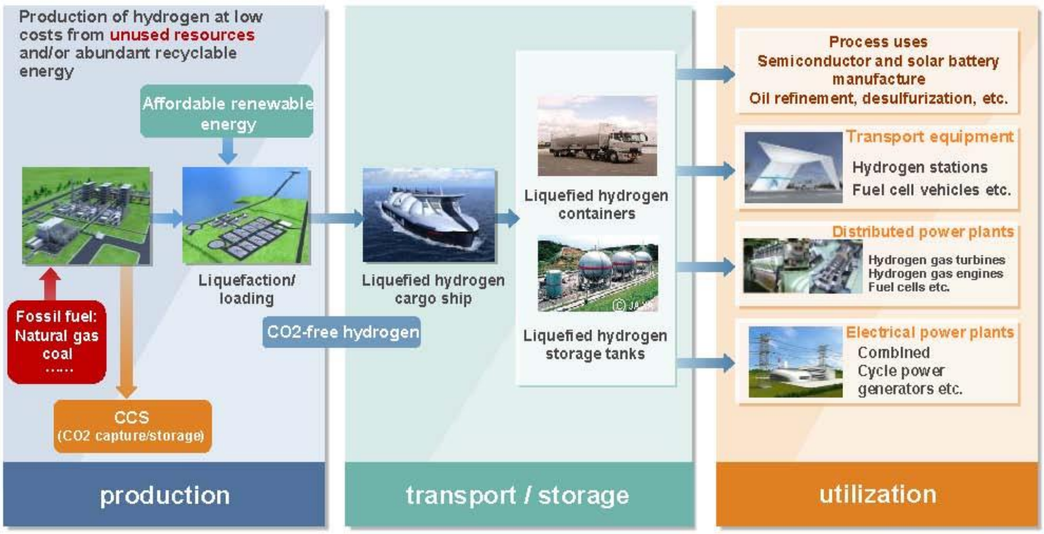
- Hydrogen can be produced from various sources and procured from many countries → Contribute to energy security
- Large amount, long-distance, long-term transportation and storage of energy and sector integration are possible with hydrogen → Contribute to resilience



Kawasaki Powering your potential 4

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

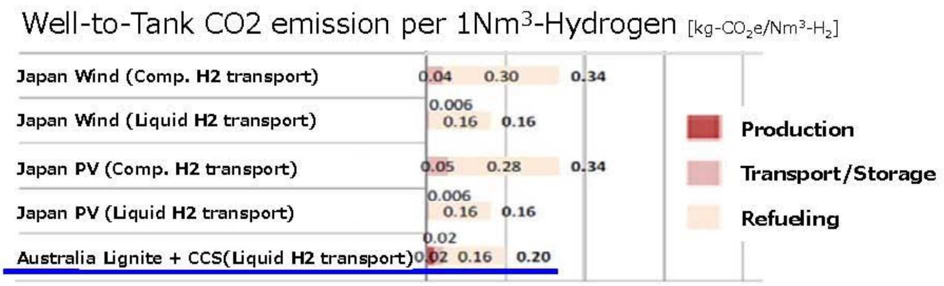
Liquefied hydrogen tanks (Tanegashima Rocket Base)

Largest liquefied hydrogen tanks in Japan (Kobe)

Commercial LH2 Carrier (Future)

LCA by Mizuho Information & Research Institute

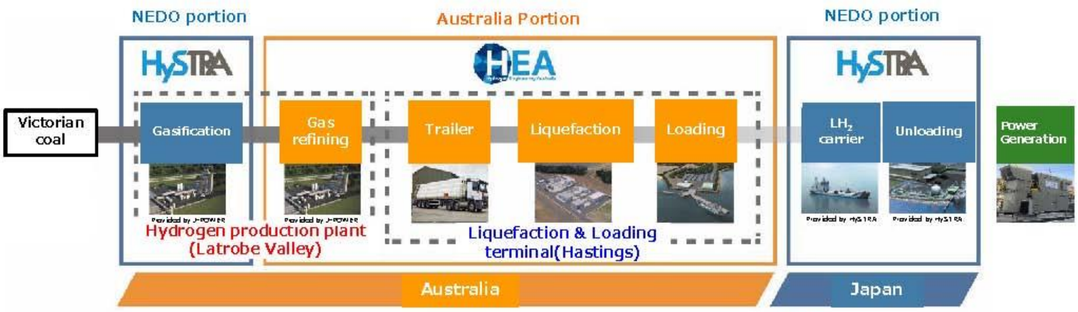
- Low CO2 emission equivalent to renewable oriented hydrogen



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)

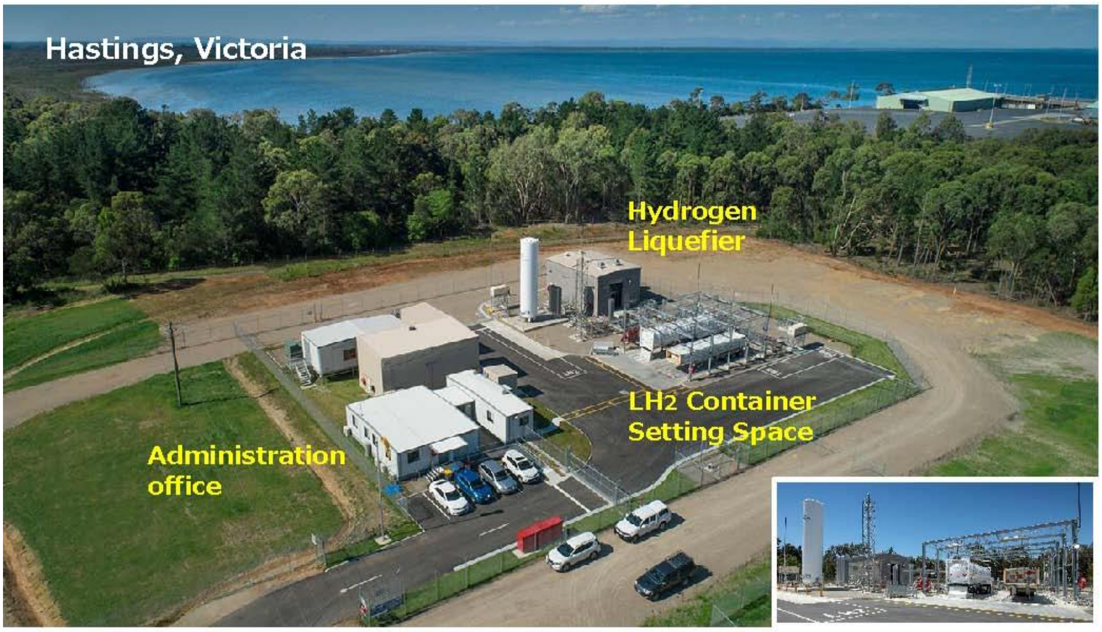
Kawasaki, Iwatani, J-Power, Shell Japan
Marubeni, ENEOS, KLINE
Supported by NEDO and METI

Hydrogen Engineering Australia (HEA)

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

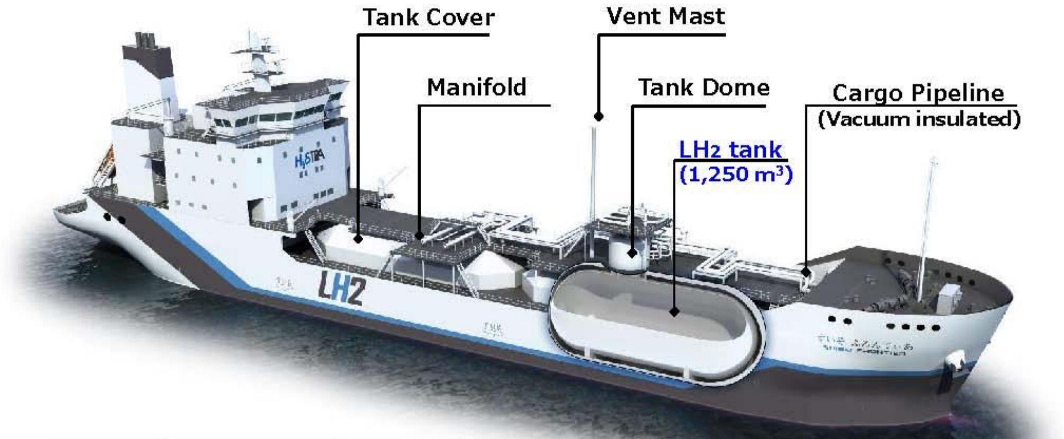
*NEDO : New Energy and Industrial Technology Development Organization
*METI: Ministry of Economy, Trade and Industry

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)

Kawasaki
Powering your potential

LH2 Receiving Terminal

LH2: Liquefied Hydrogen

Kawasaki
Powering your potential

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

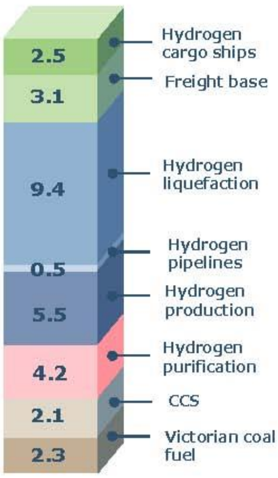
Commercial terminal tank: 50,000m^3

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

Kawasaki Powering your potential 13

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

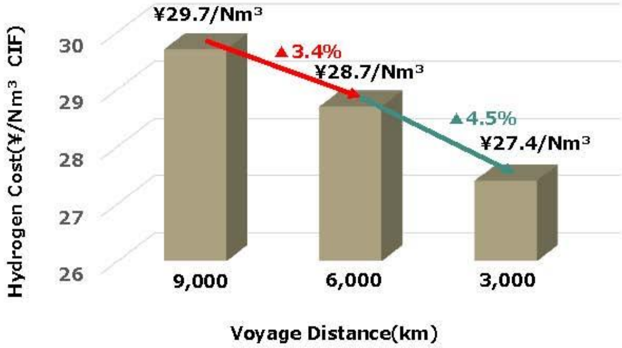
Precondition for Hydrogen Cost Calculation in 2030

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

Kawasaki Powering your potential 14

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




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

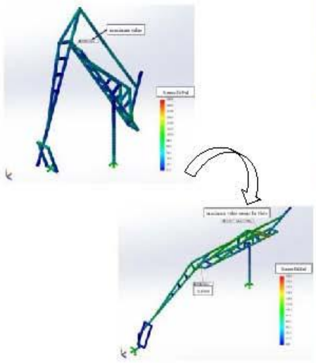
"Global Kawasaki"

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



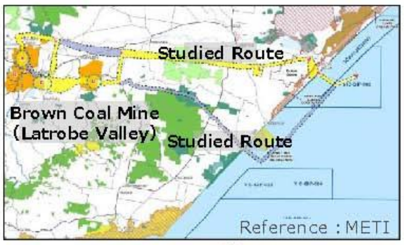
Simulation of maximum movable area

Subsidized by NEDO

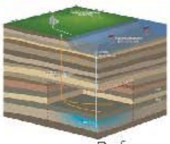
Hydrogen Gas Turbine CGS (Kobe Port Island)

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