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Demand and Supply Potential of Hydrogen Energy in East Asia

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This report was prepared by the Study Group for Hydrogen Potential Study in Asia Region, which was formulated under the Economic Research Institute for ASEAN and East Asia (ERIA). Members of the Study Group discussed and agreed to certain key assumptions and modelling approaches to enable consistent estimation, forecast, and simulation. The key assumptions and modelling approaches used in the report were decided upon by the authors and may differ from those of the specific countries’ official stances and perspectives. Therefore, the results presented in this report should not be viewed as the official national plan of the specific countries.

Preface

East Asian economies have experienced sustained concerns on the security of energy supply, especially regarding the reliance on the imports of oil and natural gas. Such is also true with ASEAN countries. The new era of renewable energy, in particular solar and wind, has the potential to relieve such concerns, since these can be harvested indigenously. However, the intermittency of these sources poses substantial challenges to the existing energy infrastructure, especially the power grid.

Hydrogen is a new energy pathway that complements the deep penetration of intermittently active renewables by providing unlimited storage potential, but it also presents itself as a zero-emissions energy source.

Importantly, as related technologies make continuous progress, together with substantial decreases in costs, hydrogen will approach commercial competitiveness to conventional energy systems. Information regarding the potential of cost reductions along the hydrogen supply chain by 2040 can be found in this report.

For the reasons above, policy makers in many countries will start giving more attention to hydrogen, keeping in mind its potential to support a new generation of energy infrastructure that could be truly zero-emission.

This timely study consists of comprehensive analyses of the hydrogen supply chain in the Asian context, highlighting its potential based on each country's energy resources, the forecasted demand and scale of production, and trading of hydrogen for energy use in each country, as well as the resulting costs and carbon emissions.

From its early stage of market development, EAS-region demand for hydrogen for energy use is estimated to reach up to 104.7 Mtoe per year by 2040. Such demand will be contributed by the power generation sector, the industry sector, and the transport sector, which uses hydrogen to replace the use of fossil fuels.

The hydrogen initiatives led by Australia, Japan, Republic of Korea, and New Zealand coincide with ASEAN's announced ambition to achieve 23% renewable energy integration into its energy system by 2025, with even more by 2030. It is thus hoped that ASEAN countries will join the global development of supply chains for hydrogen production and consumption. Some ASEAN countries have the prospects to become a prosumer of zero-emission hydrogen energy, while others to become net exporters of it.

Hidetoshi Nishimura
President of ERIA
Jakarta, April 2019

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Executive Summary

Although currently hydrogen is used for industrial activities such as ammonia production or refining, there will be big potential to be one of clean energies in future. Energy uses of hydrogen are; a. fuel for Fuel Cell Vehicle (FCV) in road transport sector, b. fuel for power generation (start from mixture with natural gas and shift to 100% hydrogen finally), c. heating fuel for boiler or furnace in industry sector. However, hydrogen is not competitive to gasoline and diesel vehicles so far due to high hydrogen price (about US90cent/Nm3 in Japan) and fuel cell vehicle (about US$70,000/car in Japan). Power generation to use hydrogen is also not competitive to Natural gas based Combined Cycle Gas Turbine (CCGT) due to the same reasons. In addition, since places for hydrogen production and consumption are different, hydrogen supply amount, such as byproduct hydrogen in importing countries, like Japan, is not enough to meet its demand in future. Consequently, establishment of international/regional hydrogen supply chain will be indispensable.

According to this research study, hydrogen supply cost of local supply chain will be forecasted to go down to US40-50cent/Nm3 on average at a station. It will be in the range in some cases, but it will be still higher on average than around US30-40cent/Nm3 which is competitive target price for gasoline. If epoch making technological development on FCVs and hydrogen power plants would be achieved, hydrogen supply cost will be expected to go down largely based on expansion of hydrogen market scale through significant price down of FCVs and hydrogen power plants.

Use of hydrogen is expanding in transport sector. So far FCVs represent personal cars but now included buses and railway trains. Regarding the buses, Tokyo Metropolitan Government will increase the hydrogen buses to 100by 2020 and Sarawak Local Government will start to operate hydrogen buses soon.

Results of the hydrogen demand forecasting to apply the three scenarios indicate to replace 2% of fossil fuels by hydrogen in 2040. On the other hand, CO2 emissions are expected to reduce 2.7% and higher than reduction of fossil fuels. The reason is to reduce coal consumption for power generation due to replacement of hydrogen.

There are two types of hydrogen production processes; a. applying reforming and gasification of fossil fuels such as natural gas and coal, b. applying water electrolysis using electricity generated by renewable energy such as hydro/geothermal, solar/PV and wind. Although on the view of CO2 emissions, the latter is recommended, hydro / geothermal power as well as reforming of natural gas will firstly be introduced to produce hydrogen due to their lower costs. Gasification of coal and solar/PV & wind might start to produce hydrogen after achievement of their cost reduction through significant technology development. However in case of fossil fuels, treatment of CO2 is very important applying CO2/EOR and CCUS. Basically solar/PV and wind need electric energy storage, currently cost of which is much expensive, to mitigate their intermittent power supply. Then hydrogen will be one of storage options because of its capability for large scale and mid-long term storage.

Hydrogen gets remarkably high evaluation recently. Japanese Government launched the Basic Hydrogen Strategy and hydrogen is now included in the 5th Basic Energy Plan of Japan. The hydrogen council released a publication namely “Hydrogen Scaling Up” to mention that hydrogen demand will be 20% of TFEC of the world in 2050. Australia and New Zealand also seek for possibility to export hydrogen to Japan. However only Brunei Darussalam and Sarawak State of Malaysia among ASEAN member states shows their interest on hydrogen because the hydrogen supply chain demonstration project is ongoing in Brunei Darussalam and introduction of hydrogen buses in Sarawak State of Malaysia. In this regard, it is recommended that a working group consisting of ASEAM and +6 members will be set up to produce common understanding on hydrogen under EAS region.

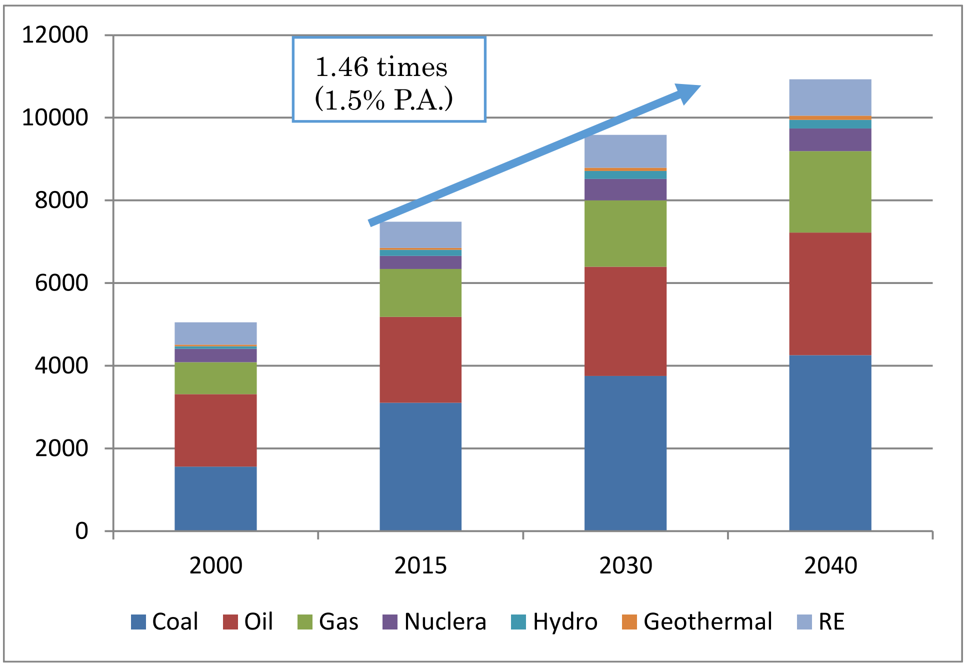
Chapter 1

Introduction

1. Energy Outlook in the East Asia Summit Region

According to the East Asia Summit (EAS) Energy Outlook produced by the Economic Research Institute for ASEAN and East Asia (ERIA), which covers ASEAN 10 countries plus Australia, China, India, Japan, Republic of Korea, New Zealand and United States, the total primary energy supply (TPES) will increase from 7,487 Mtoe in 2015 to 10,931 Mtoe in 2040. The annual growth rate will be 1.5% (1.46 times), two percentage points lower than the 3.5% per annum GDP growth rate in the same period. The share of fossil fuels will remain at more than 80% from 2015 to 2040, as shown in Figure 1.1. In this regard, CO_2 emissions will also increase 1.5% per annum, following the TPES.

Figure 1.1 Future Projection of TPES (in Mtoe)



Mtoe = million tonnes of oil equivalent, PA = per annum, RE = renewable energy, TPES = total primary energy supply.
Source: ERIA EAS Energy Outlook 2017 (2019).

Consequently, most energy policies in the EAS region promote efficiency and conservation (reduce fossil fuel consumption) and shifting to such low-carbon energies as nuclear and renewables (reduce CO_2 emissions). As a renewable energy source, hydrogen is highlighted to reduce CO_2 emissions for the following reasons:

a. **Zero CO_2 emissions**. Hydrogen bonds with oxygen to generate electricity/heat, with water as the only by-product.

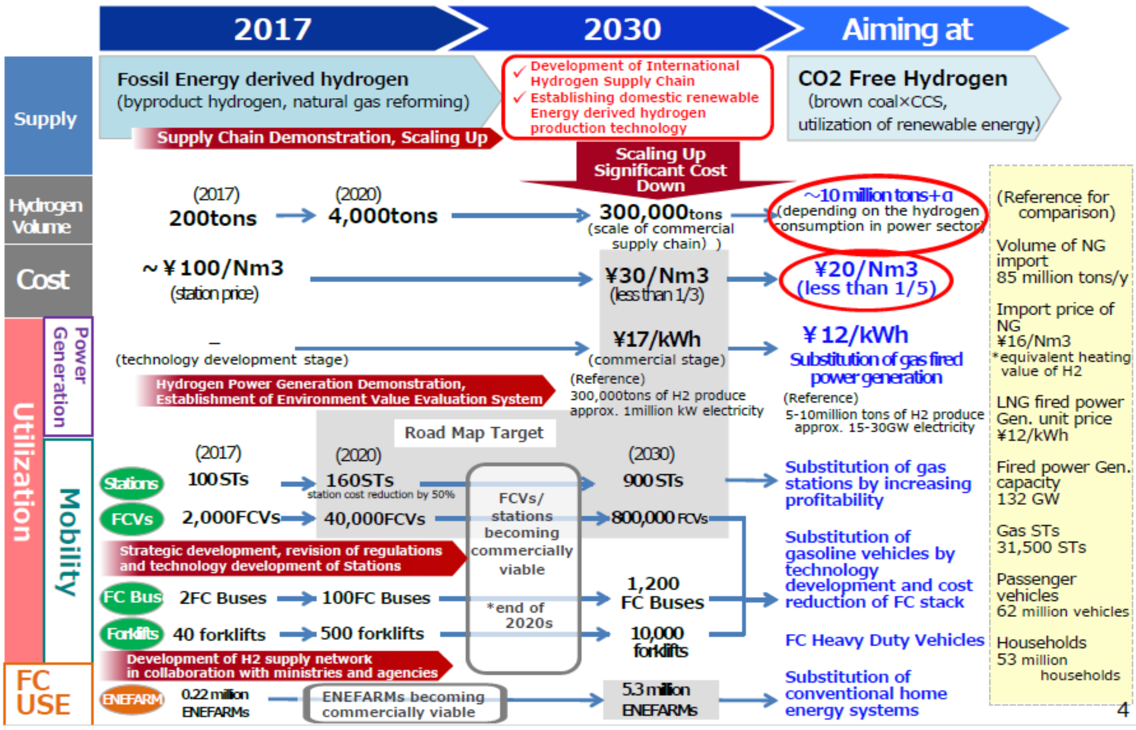
b. **Unlimited Supply**. Hydrogen can be extracted from a wide range of substances, including oil, natural gas, biofuels, and sewage sludge, and can produce unlimited natural energy by water electrolysis.

c. **Storage and transportation**. Hydrogen is able to store energy beyond the seasons and be shipped over long distances.

2. Current Trends of Hydrogen

The Ministry of Economy, Trade and Industry (METI), Japan, launched the Basic Hydrogen Strategy, as summarised in Figure 1.2. It was approved by the cabinet in December 2017, and details the action plans through 2030, as well as the future vision through 2050.

Figure 1.2 Basic Hydrogen Strategy in Japan



CCS = carbon capture and storage, FC = fuel cell, FCV = fuel cell vehicle, LNG = liquefied natural gas, NG = natural gas, STs = stations.
Source: METI, Japan (December 2017)

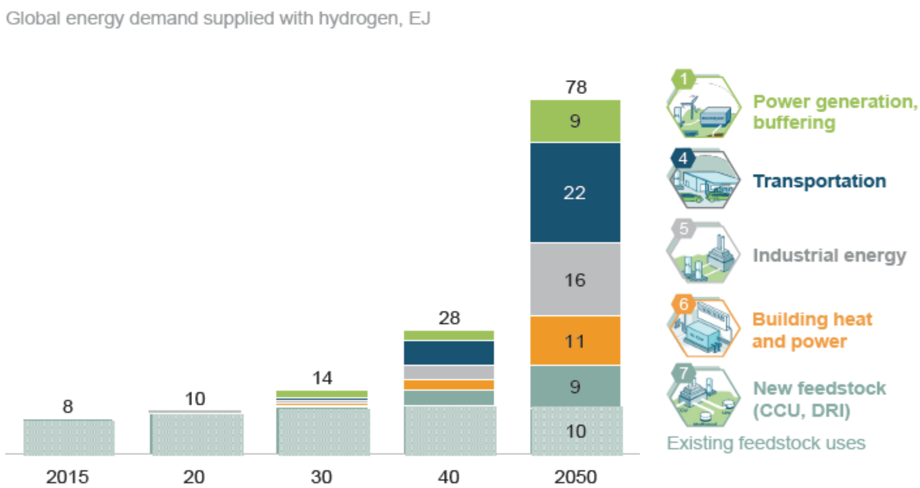
METI, Japan, also organised the First Hydrogen Energy Ministerial Meeting in Tokyo, held on 23 October 2018 (see Figure 1.3 for photo). More than 300 people from 21 countries, regions, and organisations met to discuss both demand and supply penetration of hydrogen.

Figure 1.3 Group Photo of the First Hydrogen Energy Ministerial Meeting

Source: Ministry of Economy, Trade and Industry, Japan.

In addition, the Hydrogen Council released the publication, 'Hydrogen Scaling Up' in November 2017, which mentioned that 20% of total final energy demand in 2050 will be covered by hydrogen, bringing such economic effects as more than US$2.5 trillion per year in revenue and more than 30 million people employed, as shown in Figure 1.4.

Figure 1.4 Expected Hydrogen Demand in 2050



CCU = carbon capture and utilisation, DRI = direct reduced iron.
Source: Hydrogen Council (November 2017).

In addition, Chiyoda Corporation (Chiyoda), in collaboration with Mitsubishi Corporation, Mitui & Co., Ltd., Nippon Yusen Kabushiki Kaisha, has started the world's first global hydrogen supply chain demonstration project using SPERA Hydrogen technology, funded by the New Energy and

Industrial Technology Development Organization, which will produce hydrogen in Brunei Darussalam for power generation in Japan. A maximum of 210 tonnes of hydrogen will be brought from Brunei Darussalam to Japan in 2020.

a. Scope of Work

Referring to the Energy Outlook results and the current hydrogen trends, ERIA conducted a hydrogen research study in collaboration with Chiyoda and The Institute of Energy Economics, Japan. The research contents are:

a. Review of renewable energy policies, including hydrogen
b. Forecasting future hydrogen demand potential
c. Forecasting future hydrogen supply potential
d. Well-to-wheel analysis
e. Site survey

i. Review of renewable energy polices, including hydrogen

This part reviews the existing polices on climate, renewables, and hydrogen (if available) of the following countries:

a. ASEAN 7 countries, except Cambodia, Lao People's Democratic Republic, and Myanmar due to the small potential of hydrogen demand and supply
b. Australia, China. India, Japan, Republic of Korea, New Zealand

Renewable energies, which consist of hydro power, geothermal power, solar photovoltaics and wind power, are potential sources of zero-emissions hydrogen, as detailed in chapter 4.

ii. Forecasting future hydrogen demand potential

Hydrogen will be used mainly in the following sectors:

a. Road transport (vehicle)
b. Power generation
c. Industrial heat

(1) Road transport (vehicle)

In July 2018, Japan introduced over 2,700 fuel cell vehicles (FCVs), serviced by 100 hydrogen stations, with an eventual 2025 target of 200,000 cars and 320 stations. Current FCV trends in Japan include the following:

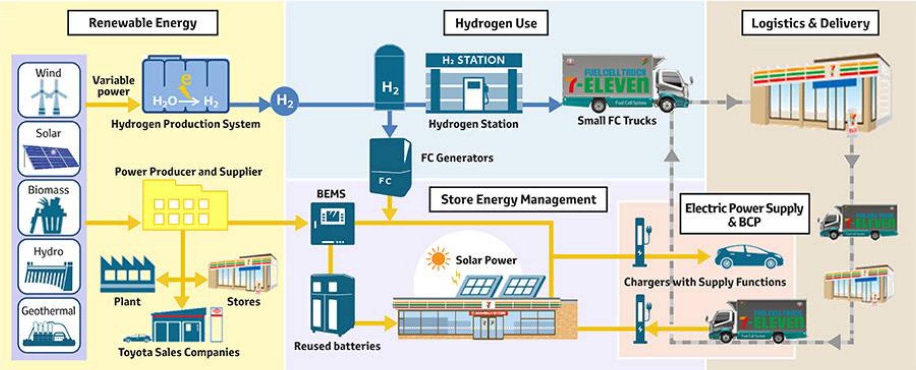
a. Joint venture for hydrogen stations

In March 2018, 11 companies (Toyota, JXTG, Tokyo Gas, etc.) established the 'JHyM' joint venture to promote an H2 station network.

b. Fuel cell trucks in '7-Eleven'

- 7-Eleven Japan and Toyota will jointly launch a next-generation convenience store project in autumn 2019.
- Small fuel cell trucks, fuel cell generators, solar panels, rechargeable batteries and BEMS will be made available in their stores and distribution.

Figure 1.5 New BEMS of '7-Eleven' Store



BCP = Business Continuity Planning; BEMS = Building Energy Management Systems; FC = fuel cell.
Source: Press release by 7-Eleven/Toyota.

c. Tokyo fuel cell buses

Tokyo introduced two fuel cell buses in March 2017 with the goal of increasing the number to 100 by the Tokyo Olympic Games in 2020.

For forecasting FCV deployment through 2040, three scenarios are applied in lieu of a single model:

a. Scenario 1: 2% of gasoline cars will be replaced by FCVs by 2040
b. Scenario 2: 10% of gasoline cars will be replaced by FCVs by 2040
c. Scenario 3: 20% of gasoline cars will be replaced by FCVs by 2040

(2) Power generation

To introduce hydrogen into power generation, gas turbine manufacturers have started demonstration/R&D for hydrogen combustion, and electric power companies have started feasibility studies to introduce hydrogen into their power plants.

a. Hydrogen gas turbine (MHPS)

   MHPS has successfully fired with a 30% hydrogen fuel mix in 2018 and will move to 100% hydrogen combustion in 2023.

b. Feasibility study for hydrogen power generation

   Japanese electric power companies KEPCO and Chuden conducted a hydrogen power generation feasibility study from 2018 to 2019.

   i. **Technical evaluation of hydrogen mix combustion**. Maximum ratio of hydrogen mix using combustor of existing gas turbine, Performance of combustion/power generation and impact for environment/durability/reliability by hydrogen mix combustion, Technical/risk analysis, related laws and regulations.

   ii. **Study of the hydrogen supply system**. Study hydrogen supply system regarding receiving, storage, supply, and fuel mix, and execute basic design at expected site.

   iii. **Basic design for hydrogen mix combustion system**. Execute basic design of hydrogen mix combustion system, based on results of technical evaluation.

   iv. **Economic evaluation**. Clarify technical challenges and evaluate future economics of hydrogen-mix power generation.

For forecasting power generation from hydrogen through 2040, three scenarios of hydrogen mixing ratios are applied in lieu of models;

a. Scenario 1: 10% hydrogen and 90% natural gas

b. Scenario 2: 20% hydrogen and 80% natural gas

c. Scenario 3: 30% hydrogen and 70% natural gas

(3) Industrial heat

We assume heating boilers and furnaces using natural gas can be replaced by hydrogen and consider one scenario:

Scenario 1: 20% natural gas will be replaced by hydrogen

iii. Forecasting future hydrogen supply potential

There are mainly two hydrogen sources:

a. Fossil fuel

b. Renewable energy

The detailed production processes are shown in Figure 1.6.

Figure 1.6 Hydrogen Production Method

HYDROGEN from Fossil Fuel

- **By-product hydrogen** (CCR, ethylene, methanol, chlor-alkali)
- **Reformed hydrogen** (flare gas, reinjection gas, mid-small gas field)
- **Gasified hydrogen** (VR/ pitch / coke, coal / lignite)

+

- **CCUS** (CO2-EOR, CCS, CO2 feedstock)

HYDROGEN from Renewable Energy

- **Water electrolysis hydrogen** (solar, wind, hydro, geothermal)
- **Biomass hydrogen** (waste, unutilized, resource crop)

< Technology Development >

- **Biotech hydrogen** (microalgae, bacterium, etc.)
- **Photo-catalyst hydrogen** (Solar)

CCR = Conradson carbon residue, CCUS = carbon capture, utilization and storage, EOR = enhanced oil recovery, VR = vacuum residue.
Source: Author.

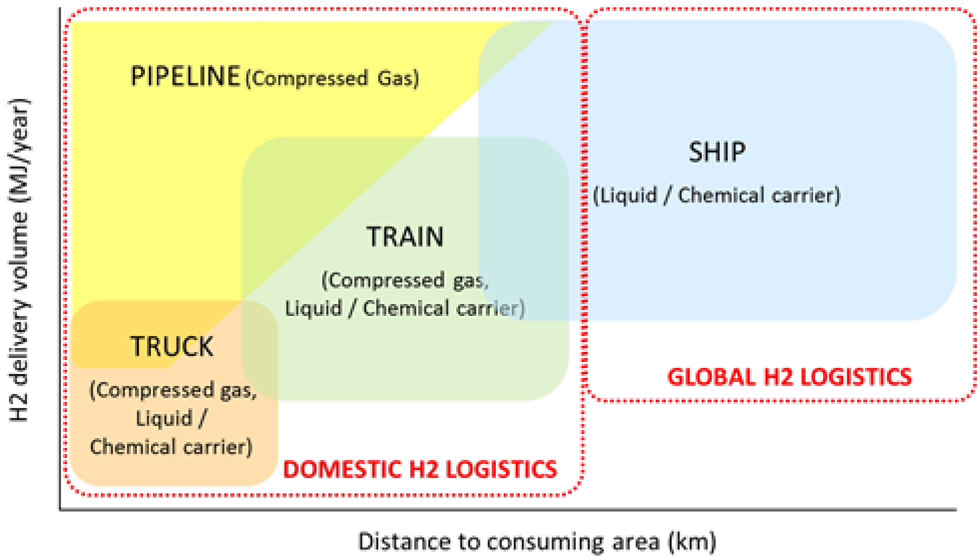
Gauging hydrogen supply potential based on proven reserves of coal (lignite), oil, and natural gas (mainly flare and mid-small size gas field) is linked to production potential forecasts. On the other hand, solar and wind potentials are forecasted using weather information such as solar radiation and wind speed. Nonetheless, some of the potentials will be used directly for electricity, so that the remainders will be used for production of hydrogen.

There are three transportation measures:

a. Ship
   Liquid hydrogen tanker, chemical tanker, container vessel, barge, etc.
b. Train
   Freight train, container train, etc.
c. Truck
   Liquid hydrogen truck, chemical/gasoline tank truck, etc.
d. Pipeline
   Hydrogen gas pipeline, natural gas pipeline, etc.

The choice of the measures depends on distance and volume, as shown in Figure 1.7:

Figure 1.7 Image of Hydrogen Logistics Portfolio



Source: Author.

In addition, the supply cost of hydrogen, including production and transportation, is examined.

iv. Well-to-wheel Analysis

Several types of vehicles, including internal combustion engine vehicles (ICEs), plug-in hybrid electric vehicles (PHEVs), battery electric vehicle (BEVs), and FCVs are compared in terms of energy consumption, CO_2 emissions, and total cost. The total cost consists of the capital cost (price of vehicle) and fuel costs (gasoline, diesel, electricity, as well as hydrogen). The energy consumption, CO_2 emission, and cost of hydrogen supply are built into the analysis based on the well-to-wheel concept. This study uses accurate cost data, but this is very difficult due to confidentiality constraints and a lack of agreed-upon measurements. For example, the FCV price in 2040 fully depends on technology development and market size.

v. Site Survey

Site surveys, i.e., information exchange meetings, were conducted with several organisations and offices regarding fossil fuels, renewable energy, and hydrogen. We visited Ministries of Energy (Policy, Oil and Gas, Renewables, including hydrogen), and national oil companies such as Pertamina, Petronas, and PTT, plus coal-mining companies and private hydrogen companies. The site survey covered the following six countries:

a. ASEAN

   Indonesia, Malaysia, Thailand

b. +6 Countries

   Australia, India, New Zealand

The meetings covered the following items:

a. introduction of this hydrogen research study, including the results
b. comments on the results
c. data collection regarding the production potential of fossil fuels, potential of CO2/EOR & CCUS
d. power development plan, especially renewable energy
e. hydrogen policies

CHAPTER 2
Hydrogen Policies in EAS countries

This chapter summarises the policies relevant to hydrogen energy, together with the potential of solar and wind energy that could possibly be used to generate zero-emissions hydrogen.

The study team has selected 13 countries from the East Asia Summit (EAS) region based on their potential for developing hydrogen energy. Each country's approach to hydrogen is different, with the governments of Australia, India, China, Japan, and Republic of Korea (henceforth Korea) having already formulated a hydrogen policy, and New Zealand set to draw a hydrogen roadmap in 2019. Though other countries lack any specific hydrogen policy as of January 2019, even in some of these, several pilot projects are being promoted.

When it comes to CO_2, power and transport account for a majority of emissions, and these are expected to increase. Hydrogen itself has various industrial uses, and can be an environmentally friendly energy source. Though hydrogen's production cost was previously thought to be prohibitive, technology is now paving the way for affordable, CO_2-free hydrogen.

This juncture in history features both an urgent need to rein in CO_2 emissions and a high priority placed on global energy security. Fortunately, the EAS region has both abundant renewable energy and untapped hydrogen energy resources. In addition to each individual country's efforts, the EAS countries should draft a communal energy point of view and collaborate on a hydrogen supply chain for the next generation.

1. Selected ASEAN member countries

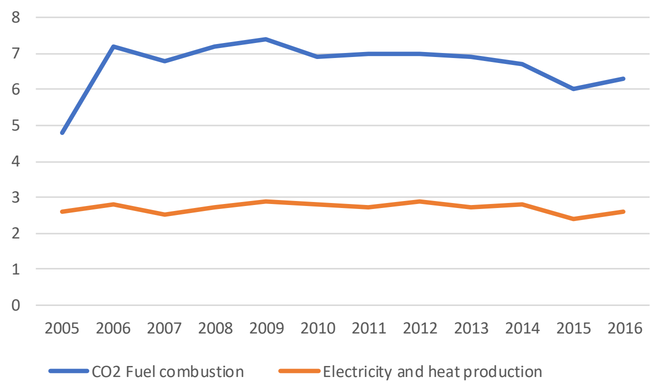
1.1. Brunei Darussalam

1.1.1. Climate policy, INDC

Brunei Darussalam's intended national determined contribution (INDC) is geared to reducing the country's total energy consumption by 63% by 2035, with 10% of total power generation sourced from renewables.

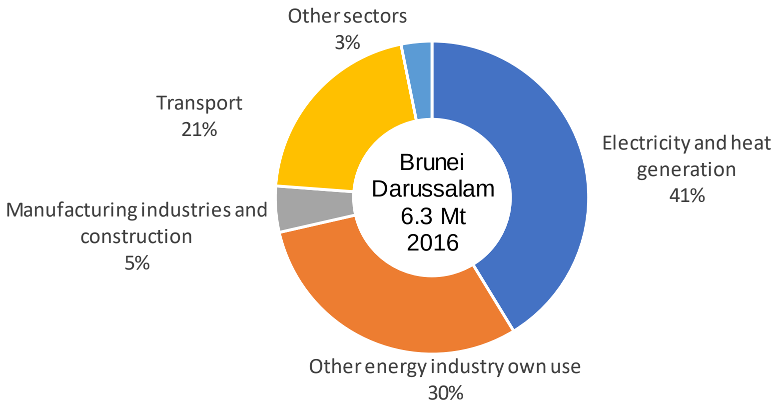
As shown in Figure 2.1, Brunei Darussalam's CO_2 emissions have generally been declining since 2009. Figure 2.2 shows how electricity and heat production in 2016 accounted for 41% of total CO_2 emissions, followed by other energy industry's own use for another 30% (UNFCCC, 2015).

Figure 2.1 CO_2 Emissions from Fuel Combustion (2005–2016)



Source: International Energy Agency, CO_2 Emissions from Fuel Combustion 2018.

Figure 2.2 CO_2 Emissions by Sector (2016)



Source: International Energy Agency, CO_2 Emissions from Fuel Combustion 2018

1.1.2 Renewable energy and hydrogen policy

1) Renewable energy policy

The Brunei Darussalam Prime Minister's office issued an energy white paper in 2014 (Energy Department, Brunei Darussalam, 2014), which detailed its four renewables initiatives:

(a) Introduce renewable energy policy and regulatory frameworks;

(b) Scale-up market deployment of solar photovoltaics and promote waste-to-energy technologies;

(c) Raise awareness and promote human capacity development; and

(d) Support research, development and demonstration and technology transfer.

The Prime Minister's office also set a key performance indicator for renewable energy, as shown in Table 2.1:

Table 2.1 Key Performance Indicator for Renewable Energy

Key Performance Indicator	Unit	2010 baseline	2017	2035
Power generation from renewable sources of energy	MWh	808	124,000	954,000

Source: Brunei Darussalam Energy White Paper.

2) Potential of solar and wind energy

The United Nations Food and Agriculture Organization's 2011 renewables survey for Brunei Darussalam indicated 18.9 MJ/m^2/day of solar radiation and 372 MW of potential offshore wind power (Malik, 2011).

3) Hydrogen policy

The Advanced Hydrogen Energy Chain Association for Technology Development (AHEAD) has started a project to deliver hydrogen fuel to Japan. AHEAD is composed of four Japanese companies that have an interest in hydrogen and fuel cell technology sourced from Brunei Darussalam. This supply is meant to help Japan establish a functioning hydrogen society (Chiyoda Corporation, 2018). The project has completed a process for intergovernmental cooperation and involves building a new hydrogen production facility in Brunei Darussalam. The facility is expected to begin operation in January of 2020 and will be active for a year while its capabilities are assessed, with the hydrogen produced delivered to another plant in Japan and supplied to customers and businesses. Once fully operational, the facility is expected to provide Japan with enough hydrogen to power some 40,000 fuel cell vehicles.

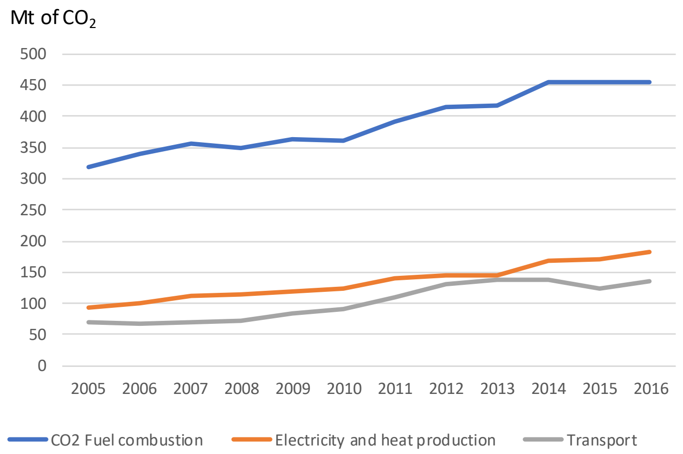
1.2 Indonesia

1.2.1 Climate policy, INDC

Indonesia is committed to reducing its greenhouse gases by 29% from its current baseline by 2030. Reduction will be increased to 41% if international cooperation is provided.

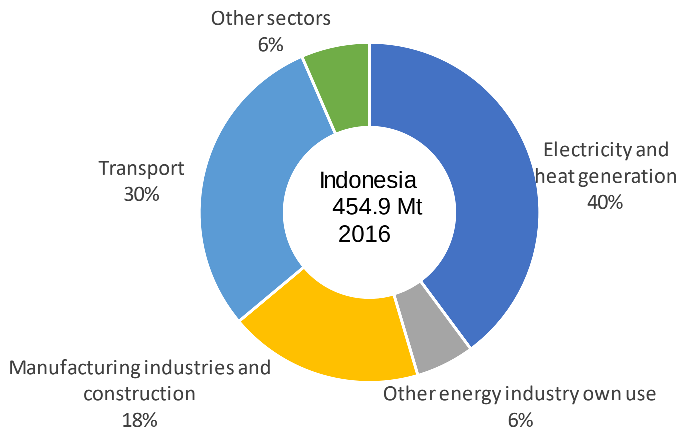
As shown in Figure 2.3, CO_2 emissions have been steadily on the rise, having increased by 43% from 2005 to 2016. Figure 2.4 shows how electricity and heat production accounts for 40% of 2016 CO_2 emissions in Indonesia, followed by transport with 30% (UNFCCC, 2015).

Figure 2.3 CO_2 Emissions from Fuel Combustion (2005–2016)



Source: International Energy Agency, CO_2 Emissions from Fuel Combustion 2018.

Figure 2.4 CO_2 Emissions by Sector (2016)



Source: International Energy Agency, CO_2 Emissions from Fuel Combustion 2018.

1.2.2 Renewable and hydrogen energy policy

1) Renewable energy policy

Indonesia enacted its National Energy Policy in 2014 (Government Regulation No. 79/2014) (IEA, 2018). The policy aims to transform the energy mix to 23% renewables by 2025 and 31% by 2050 (see Table 2.2 for further details).

Regarding solar power, on 16 November 2018, Energy and Mineral Resources Minister Ignasius Jonan issued Ministerial Regulation 29/2018 on the use of electricity produced through rooftop solar photovoltaic panels for customers of the state-owned electricity company PLN (Jakarta Post, 2018). Furthermore, the Ministry's director general for renewable energy, Rida Mulyana, said on 28 November 2018 that the government expected rooftop solar photovoltaic panels to produce 1 GW of electricity nationwide within 3 years.

Table 2.2 Target of Renewable Energy Development (in GW)

Type	Capacity power plants		
	Committed (in 2016)	2025 Target	2050 Target
Geothermal	7.242	7.242	17.5
Hydro	15.559	20.987	45.0
Bioenergy	2.006	5.500	26.1
Solar	0.540	6.500	45.0
Wind	0.913	1.800	28.6
Other energy	0.372	3.125	6.4
Total	26.631	45.153	168.6

Source: Otoritas Jasa Keuangan OJK (2017).

Every year, the Ministry of Energy and Mineral Resources announces the Electricity Supply Business Plan for the next 10 years. The latest plan for 2018–2027 estimates additional power capacity, as shown in Table 2.3 (ESDM, 2018).

Table 2.3 Additional Power Capacity 2018–2027

Type of Power Plant	Allocated Capacity (GW)	Percentage
Coal-fired Power Plant	26.8	47.8
Gas-fired Power Plant	14.2	25.4
Hydro Power Plant	4.8	8.6
Geothermal Power Plant	4.6	8.2
Others	5.5	9.8
Total	56	100

Note: Others include biomass, biogas, solar (3.4 GW), etc.
Source: ESDM, 2018.

2) Potential of solar and wind energy

Indonesia has significant solar radiation resources, with 4.8 kWh/m^2/day. The country's lengthy coastlines and consistent ocean breezes are thought to have huge potential for offshore wind. The Ministry of Energy and Mineral Resources has estimated 208 GW of potential solar power and 60.6 GW of potential wind power (*ESDM*, 2017).

3) Hydrogen policy

Indonesia has not drafted a specific hydrogen policy as of December 2018. To reduce its oil imports and maintain its liquid natural gas export position, Indonesia promotes renewables in addition to gas and coal exploration. Facing fast-growing automotive fuel consumption, the country is promoting biofuels and electric vehicles and will start hydrogen vehicle development.

Regarding hydrogen utilisation for power generation in Indonesia, Toshiba Energy Systems & Solutions Corporation (Toshiba ESS) announced on August 2018 that it has concluded a memorandum of understanding (MOU) with Badan Pengkajian dan Penerapan Teknologi (BPPT), an Indonesian government organisation, on the implementation of the renewables-based H2One™ autonomous off-grid hydrogen energy system. Under the MOU, Toshiba ESS and BPPT will study the installation site, the optimum system specifications, and the operation system, including maintenance, and aim to install the first system by 2022 (Toshiba 2018a).

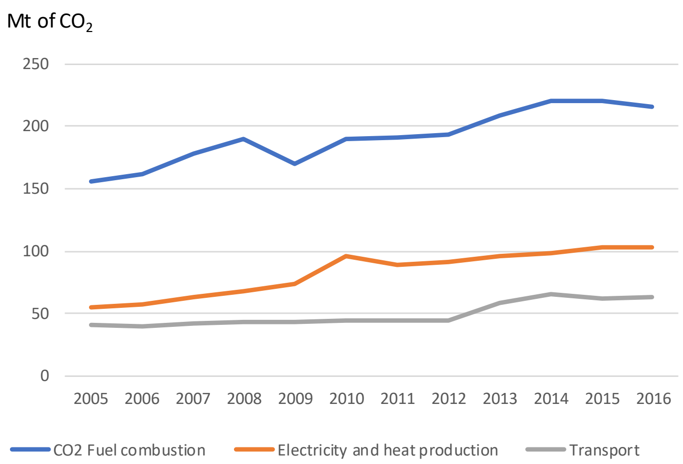
1.3 Malaysia

1.3.1 Climate policy, INDC

Malaysia intends to reduce its greenhouse gases by 45% by 2030 relative to the emissions intensity of GDP in 2005. This consists of a 35% unconditional reduction and a further 10% reduction conditional upon receipt of climate finance, technology transfer, and capacity building from developed countries.

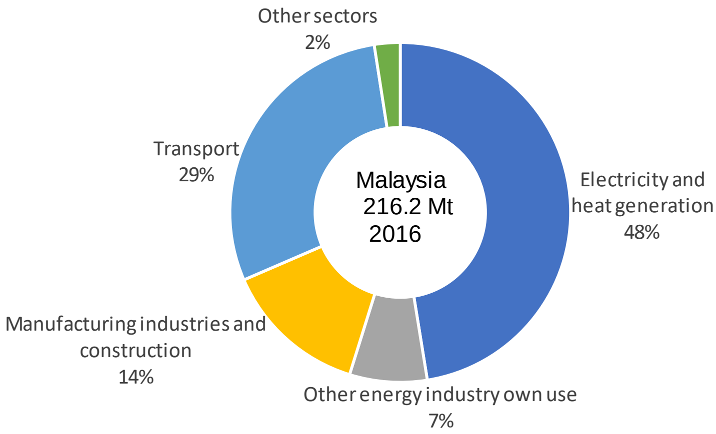
As shown in Figure 2.5, CO_2 emissions have been steadily on the rise in Malaysia, having increased 61% from 2005 to 2016. As shown in Figure 2.6, electricity and heat production accounts for 48% of total CO_2 emissions, followed by transport with another 29%. Especially, electricity and heat production have increased over the last decade (UNFCCC, 2015).

Figure 2.5 CO_2 Emissions from Fuel Combustion (2005–2016)



Source: International Energy Agency, CO_2 Emissions from Fuel Combustion 2018.

Figure 2.6 CO_2 Emissions by Sector (2016)



Source: International Energy Agency, CO_2 Emissions from Fuel Combustion 2018.

1.3.2 Renewable energy and hydrogen policy

1) Renewable energy policy

In 2017, Malaysia's Ministry of Energy, Green Technology and Water formulated its Green Technology Master Plan Malaysia 2017-2030 (Malek, 2017), which detailed the following three power sector goals:

(a) Renewable energy generation capacity will be expanded to 25% in 2025 and 30% in 2030 (see Figure 2.7);

(b) In order to increase power generation efficiency, Malaysia will introduce highly efficient coal-fired power and promote cogeneration; and

(c) Residential and commercial energy consumption will be reduced by 10% in 2025 and 15% by 2030.

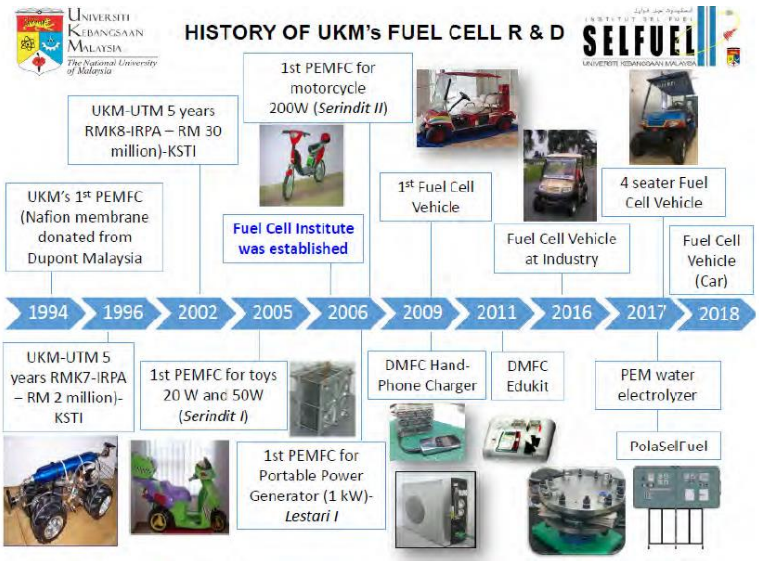
2) Potential for solar and wind energy

Malaysia is ideally suited for solar energy, with an average solar radiation of 400–600 MJ/m^2 per month (CleanMalaysia, 2016). On the other hand, the potential for wind energy has traditionally been recognised as low. However, studies have shown that offshore sites exhibit exploitable conditions for power generation, with average annual wind speeds of 4.1 m/s being recorded in the eastern Peninsula region (Reegle, 2015).

3) Hydrogen policy

In 2005, Fuel Cell Institute of Universiti Kebangsaan Malaysia formulated a hydrogen energy R&D roadmap.[1] However, due to the government changing, the roadmap was not utilised. On the other hand, since then, blueprints related to hydrogen have been published by academia in 2013 and 2017, as shown in Figure 2.7.

Figure 2.7 History of Fuel Cell R&D at the National University of Malaysia



UKM = National University of Malaysia.
Source: The 4th meeting of hydrogen potential, 10 January 2019.[2]

At present, the Sustainable Energy Development Authority (SEDA) is responsible for developing renewables, including hydrogen. However, SEDA has not incorporated hydrogen into its current energy development plan.

[1] http://aspheramedia.com/wp-content/uploads/2015/12/5e_9_01.pdf (accessed November 2018).

[2] Document of The National University of Malaysia obtained by Chiyoda Corporation.

In terms of a provincial initiative, Sarawak Energy, a utility company owned by Sarawak State, is building a pilot hydrogen production plant and refuelling station to evaluate their viability and fuel cells to power the local transportation sector in the future. Scheduled for completion in June 2019, this will be a dedicated refuelling station for transportation in Southeast Asia (Ten, 2018). Hydrogen fuel buses are expected to make their debut on the roads of Kuching city in March 2019. Sarawak's light rail transit system will use hydrogen fuel cell trains starting in 2024. The state is also looking into exporting hydrogen and scientific research is enabling transporting hydrogen almost in the same manner as liquid natural gas cylinders (FuelCellsWork, 2018).

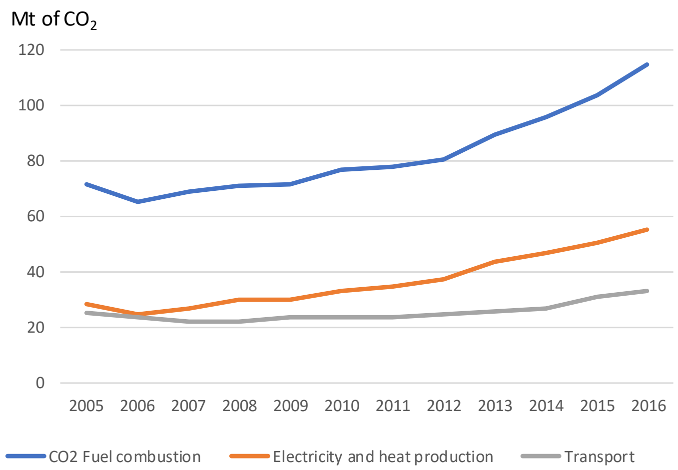
1.4 Philippines

1.4.1 Climate policy, INDC

The Philippines aims to reduce greenhouse gas emissions by about 70% by 2030 relative to its baseline scenario of 2000–2030.

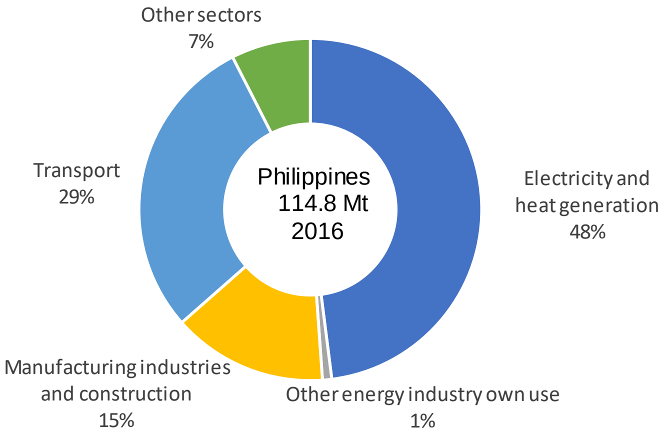
As shown in Figure 2.8, CO_2 emissions have been steadily on the rise in the Philippines, having increased 39% from 2005 to 2016. As shown in Figure 2.9, electricity and heat production accounts for 48%, followed by transport with another 29% (UNFCCC, 2015).

Figure 2.8 CO_2 Emissions from Fuel Combustion (2005–2016)



Source: International Energy Agency, CO_2 Emissions from Fuel Combustion 2018.

Figure 2.9 CO_2 Emissions by Sector (2016)



Source: International Energy Agency, CO_2 Emissions from Fuel Combustion 2018.

1.4.2 Renewable energy and hydrogen policy

1) Renewable energy policy

As shown in Table 2.4, the Philippines looks to increase its renewables-based power generation capacity to an estimated 15,304 MW by 2030, almost triple its 2010 level (DoE, 2019). The plan also intends to increase installed renewables capacity to at least 20,000 MW by 2040. To achieve these goals, the Department of Energy drafted its 'Renewable Energy Roadmap 2017-2040' (DoE, 2018).

Table 2.4 Capacity Addition of Renewable Power Generation by 2030(in MW)

Sector	Installed capacity as of 2010	Target capacity addition by				Total capacity addition 2011-2030	Total installed capacity by 2030
		2015	2020	2025	2030		
Geothermal	1,966.0	220.0	1,100.0	95.0	80.0	1,495.0	3,461.0
Hydro	3,400.0	341.3	3,161.0	1,891.8	0.0	5,394.1	8,724.1
Biomass	39.0	276.7	0.0	0.0	0.0	276.7	315.7
Wind	33.0	4,018.0	855.0	442.0	0.0	2,345.0	2,378.0
Solar	1.0	269.0	5.0	5.0	5.0	284.0	285.0
Ocean	0.0	0.0	35.5	35.0	0.0	70.5	70.5
Total	5,438.0	2,155.0	5,156.5	2,468.8	85.0	9,865.3	15,304.3

Source: Department of Energy, Republic of the Philippines, 2017.

2) Potential of solar and wind energy

Situated just above the equator, the Philippines has great solar energy potential. According to the Philippine Energy Security Plan, nationwide solar radiation has a potential annual average of 5.0–5.1 kWh/m^2/day. Solar potential is greatest from May to July, while the least insolation occurs between November and January.

In terms of wind energy, the National Renewable Energy Laboratory findings indicate over 10,000 km^2 of land area, equivalent to about 76,600 MW, with good to excellent wind potential (APCTT, 2018).

3) Hydrogen policy

The Philippines has not drafted a specific hydrogen policy as of December 2018. As outlined in its 'Energy Policy 2017-2040', the Department of Energy will embark on activities in line with the identified strategies throughout the planning period. The Alternative Fuels and Energy Technologies Roadmap 2017-2040 consists of three stages, Short-term (2017–2018), Medium-term (2019–2022) and Long-term (2023–2040) (DoE 2017). Preparation of the regulatory and infrastructure requirements of identified alternative fuels and technologies will be laid out by 2023–2040, and alternative fuel vehicles are expected to be mainstreamed in the country's transportation sector.

Furthermore, the government plans to install a CO_2-free hydrogen energy system for remote islands. On October 2018, the National Electrification Administration, a government organisation, concluded an MOU with Toshiba Energy Systems & Solutions Corporation on the implementation of the renewables-based H2One™ autonomous off-grid hydrogen energy system. Under the MOU, Toshiba and the National Electrification Administration will study the installation site, and determine the optimum local system specifications and the operation system, including maintenance (Toshiba, 2018b).

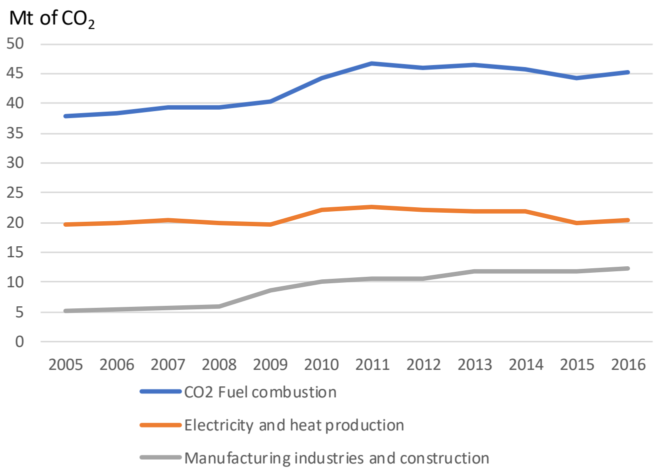
1.5 Singapore

1.5.1 Climate policy, INDC

Singapore plans to reduce its greenhouse gas emissions by 36% from its 2005 baseline by 2030 and stabilise its emissions with the aim of peaking around 2030.

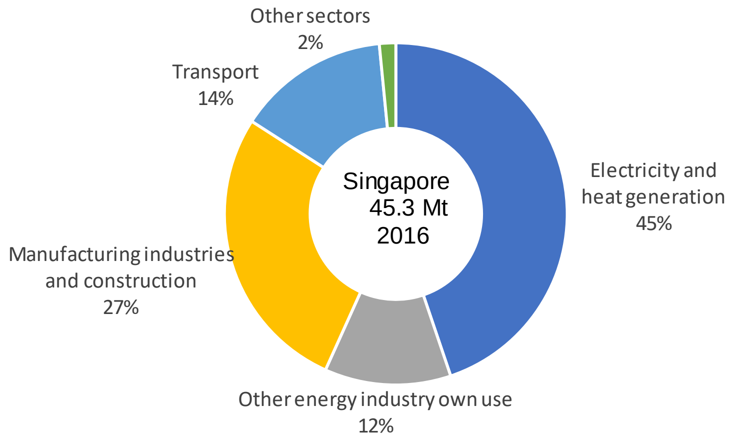
As shown in Figures 2.10 and 2.11, CO_2 emissions have generally been levelling off since 2011, with electricity and heat production accounting for 45% of the 2016 total, followed by manufacturing, industries and construction for another 27% (UNFCCC, 2015).

Figure 2.10 CO_2 Emissions from Fuel Combustion (2005–2016)



Source: International Energy Agency, CO_2 Emissions from Fuel Combustion 2018.

Figure 2.11 CO_2 Emissions by Sector (2016)



Source: International Energy Agency, CO_2 Emissions from Fuel Combustion 2018.

1.5.2 Renewable energy and hydrogen policy

1) Renewable energy policy

In 2014, Singapore released its 'Sustainable Singapore Blueprint 2015,' which outlined plans to generate 350 MW of solar power by 2020. In June 2017, the Deputy Prime Minister of Singapore, Mr. Teo Chee Hean, said that the government plans to raise solar power capacity to 1 GW beyond 2020, representing about 15% of peak electrical power demand during the day (Bhunia, 2017).

2) Potential for solar and wind energy

Singapore's solar power potential is estimated around 2 GW (Hicks, 2017). In a further development, the Singapore Housing Board is set to collaborate with a landscaping firm for the development of a floating solar system for coastal marine conditions (Tan, 2018). On the other hand, wind power potential is thought to be limited.

3) Hydrogen policy

Singapore has not drafted a specific hydrogen policy as of December 2018; however, Engie SA and other firms have experimented with storing renewables, and they plan to build a renewables storage system with hydrogen molecules on Semakau Island (Murtaugh, 2017).

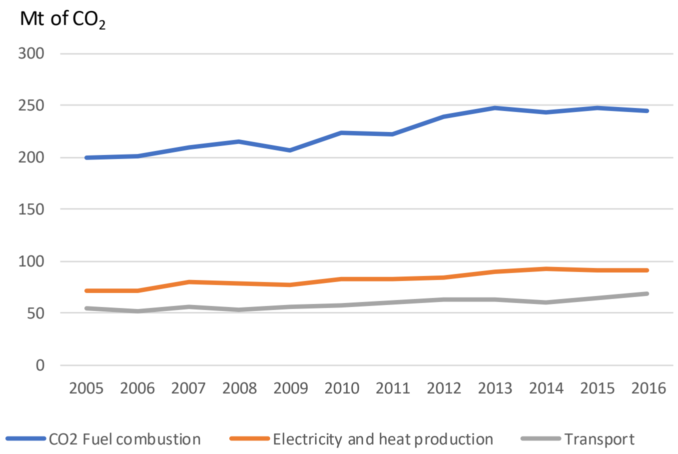
1.6 Thailand

1.6.1 Climate policy, INDC

Thailand intends to reduce its greenhouse gas emissions by 20% from the current baseline by 2030. This level of reduction could increase to 25%, subject to enhanced access to technology development and transfer, financial resources, and capacity building support through a balanced and ambitious global agreement under the United Nations Framework Convention on Climate Change.

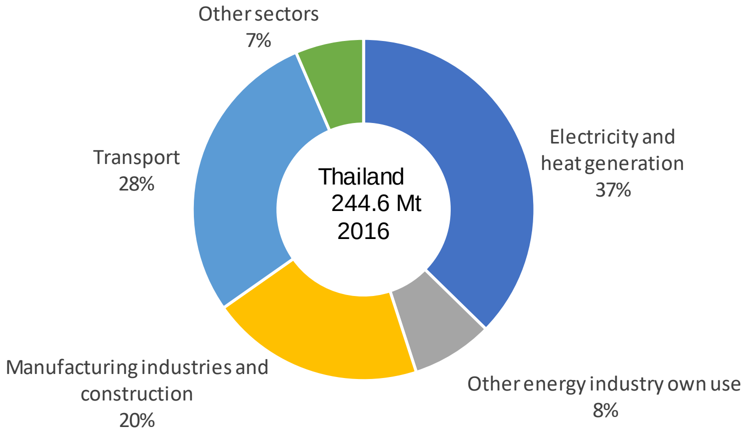
As shown in Figure 2.12, Thailand's CO_2 emissions have been steadily on the rise, having increased 22% from 2005 to 2016. As shown in Figure 2.13, electricity and heat production accounts for 37%, followed by transport for another 28% (UNFCCC, 2015).

Figure 2.12 CO_2 Emissions from Fuel Combustion (2005–2016)



Source: International Energy Agency, CO_2 Emissions from Fuel Combustion 2018.

Figure 2.13 CO_2 Emissions by Sector (2016)



Source: International Energy Agency, CO_2 Emissions from Fuel Combustion 2018.

1.6.2 Renewable energy and hydrogen policy

1) Renewable energy policy

As shown in Table 2.5, Thailand has formulated an 'Alternative Energy Development Plan 2015-2036' that targets 30% renewables in total energy consumption by 2036 (Achawangkul, 2017b).

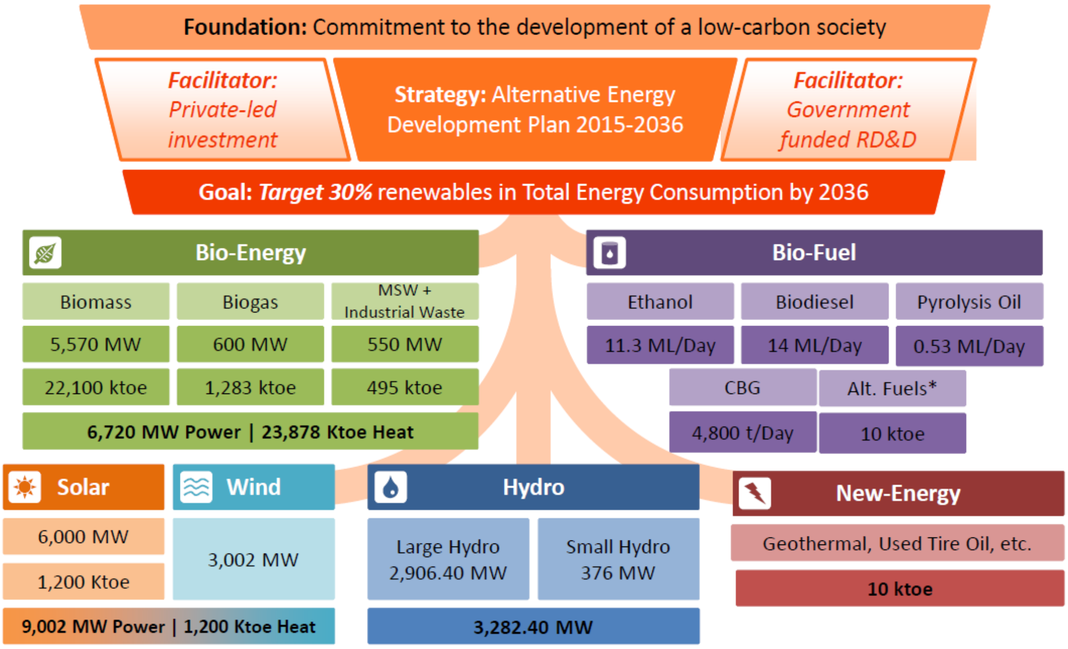
Table 2.5 Renewables Targets by 2036

Target	ktoe
RE consumption	39,388.67
Final energy consumption	131,000
RE share (%)	30%

ktoe = thousand tonnes of oil equivalent, RE = renewables.
Source: Alternative Energy Development Plan 2015–2036.

The plan outlines Thailand's renewable targets toward 2036, as shown in Figure 2.14:

Figure 2.14 Structure of Alternative Energy Development Plan 2015–2036



*Alternative fuels = Bio-oil, Hydrogen.
CBG = compressed biogas, ktoe = thousand tonnes of oil equivalent, MSW = municipal solid waste.
Source: Alternative Energy Development Plan 2015–2036.

- National Power Development Plan

In January 2019, Thailand's National Energy Policy Council approved the new version of its power development plan (PDP) 2018–2037. The PDP can be revised every 5 years as changes and technological trends occur in the power sector. The new PDP provides for additional power capacity of 56,431 MW till 2037, up from 46,090 MW in 2017. Of the increased capacity, 20,766 MW is set to be generated by renewable energy (Pugnatorius, 2019). A new version of the 'Alternative Energy Development Plan' has not been released as of January 2019.

2) Potential for solar and wind generation

The Ministry of Energy's Department of Alternative Energy Development and Efficiency has estimated the potential of solar power to be around 42 GW. Regarding wind potential, areas in which the average wind speed is greater than 6 m/s have potential for power generation of around 14 GW (Achawangkul, 2017a).

3) Hydrogen policy

Thailand has yet to draft a hydrogen policy as of December 2018. In the 'Alternative Energy Development Plan 2015-2036', hydrogen is just referred to as one of several alternative fuels (Bangkok Post, 2018).

Meanwhile, as a move toward utilising hydrogen, Phi Suea House in Chiang Mai hosted the Hydrogen Energy Summit in January 2018 to lay the foundation stone of the Green Hydrogen Refuelling Station in Southeast Asia. Developed by CNX Construction and owned by Sebastian-Justus Schmidt, the Phi Suea House is powered entirely by a solar-hydrogen system, a world's first for energy storage of its size. The solar-powered hydrogen storage system provides 24-hour, year-round access to clean energy, even during periods of bad weather (Phi Suea House, 2019).

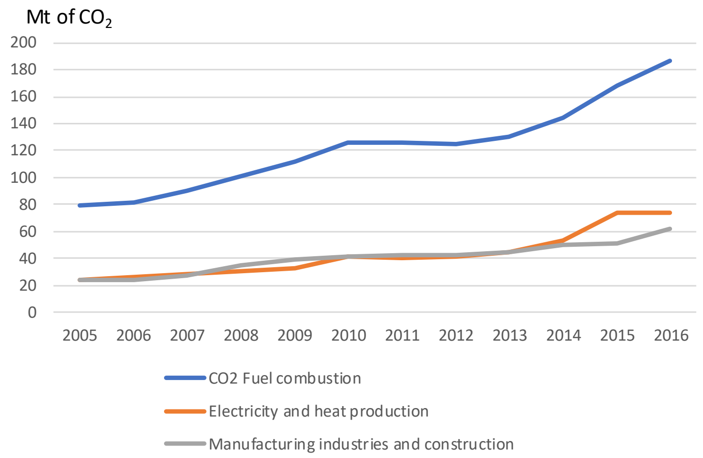
1.7 Viet Nam

1.7.1 Climate policy, INDC

Viet Nam intends to reduce its greenhouse gas emissions by 8% compared to its baseline level by 2030. The reduction could increase up to 25% if international support is received through bilateral and multinational mechanisms under the Global Climate Agreement.

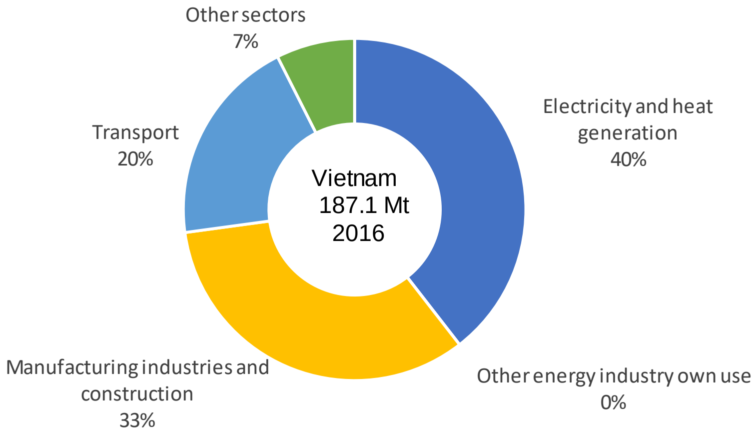
As shown in Figure 2.15, CO_2 emissions have been steadily on the rise, having increased 37% from 2005 to 2016. As shown in Figure 2.16, electricity and heat production accounts for 40%, followed by manufacturing, industries and construction for another 33% (UNFCCC, 2015).

Figure 2.15 CO_2 Emissions from Fuel Combustion (2005–2016)



Source: International Energy Agency, CO_2 Emissions from Fuel Combustion 2018.

Figure 2.16 CO_2 Emissions by Sector (2016)



Source: International Energy Agency, CO_2 Emissions from Fuel Combustion 2018.

1.7.2 Renewable energy and hydrogen policy

1) Renewable energy policy

Viet Nam's 'Revision of National Power Development Plan' details its plans to increase wind power from the current 140 MW to about 800 MW in 2020, about 2,000 MW in 2025, and about 6,000 MW in 2030 (Vietnam Electricity, 2016). Viet Nam also plans to increase solar power capacity from the current negligible rate up to about 850 MW in 2020, about 4,000 MW in 2025, and about 12,000 MW by 2030. The percentage of production from solar energy will be about 0.5% in 2020, about 1.6% in 2025, and about 3.3% in 2030.

Furthermore, Prime Minister Phuc said on June 2018 that Viet Nam will increase the electricity output produced from renewable sources from approximately 58 billion kWh in 2015 to 101 billion kWh by 2020, and 186 billion kWh by 2030 (Pearson and Vu, 2018).

2) Potential for solar and wind energy

A support programme for the Ministry of Industry and Trade sponsored by the German Corporation for International Cooperation indicates that the country has a solar power potential of 130 GW and a wind power potential of 27 GW (MOIT, 2016).

3) Hydrogen policy

Viet Nam has yet to draft a hydrogen policy as of December 2018. Any movement related to utilising hydrogen has not been observed at present.

2. Other EAS countries

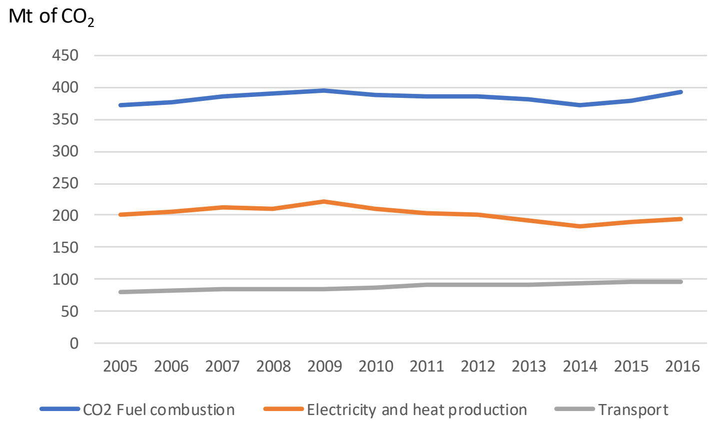
2.1 Australia

2.1.1 Climate policy, INDC

Under the Paris climate agreement, Australia has committed to reducing greenhouse gas emissions by 26% to 28% from 2005 levels by 2030.

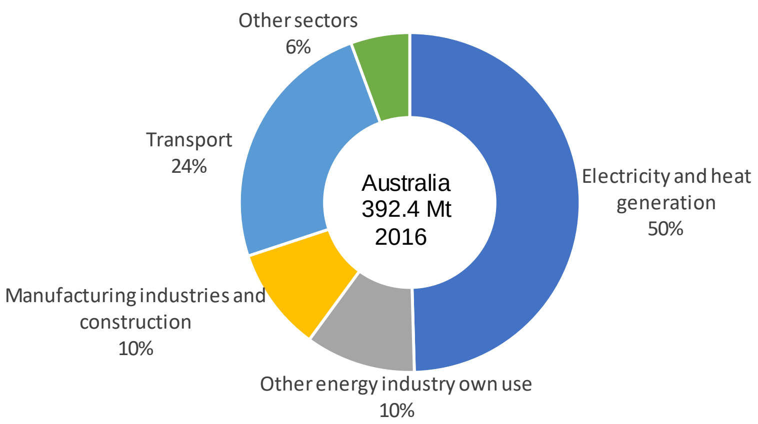
As shown in Figure 2.17, CO_2 emissions have increased 6% from 2005 to 2016. As shown in Figure 2.18, electricity and heat production accounts for 50%, followed by transport for another 24%.

Figure 2.17 CO_2 Emissions from Fuel Combustion (2005–2016)



Source: International Energy Agency, CO_2 Emissions from Fuel Combustion 2018.

Figure 2.18 CO_2 Emissions by Sector (2016)



Source: International Energy Agency, CO_2 Emissions from Fuel Combustion 2018.

2.1.2 Renewable energy and hydrogen policy

1) Renewable energy policy

Australia's Renewable Energy Target includes a scheme that mandates the production of 33 TWh of renewable energy (or 23.5% of the electricity mix) by 2020. The former government's energy policy, National Energy Guarantee (Department of Energy and the Environment, Government of Australia, 2018), was abolished in October 2018, with the country's new energy policy being discussed at the Council of Australian Governments (Hannam, 2018).

The report 'Australian Energy Projections to 2049-50', released in 2014, projects electricity generation by sector as shown in Table 2.6 (Department of Industry, Innovation and Science, Government of Australia, 2014).

Table 2.6 Projection of Electricity Generation (in TWh)

Energy type	2014-15	2034-35	2049-50	% share 2014-15	% share 2049-50	% average annual growth 2014-15 to 2049-50
Non-renewables	**216**	**252**	**265**	**85**	**80**	**0.6**
Coal	163	200	214	64	65	0.8
black coal	117	153	163	46	49	1.0
brown coal	47	47	51	18	15	0.3
Gas	50	49	48	19	14	-0.1
Oil	3	3	3	1	1	0.0
Renewables	**39**	**63**	**67**	**15**	**20**	**1.5**
Hydro	19	19	18	7	6	-0.1
Wind	16	32	33	6	10	2.0
Bioenergy	2	5	6	1	2	3.7
Solar	2	3	6	1	2	3.0
Geothermal	0	4	4	0	1	
Total a	**255**	**315**	**332**	**100**	**100**	**0.8**

Source: Australian Energy Projections to 2049–2050.

2) Potential of solar and wind energy

Australia's Renewable Energy Agency says that its annual solar radiation is approximately 58 million petajoules, approximately 10,000 times Australia's annual energy consumption Australian Energy Resource Assessment (2010). Roughly, 58 million petajoules are the equivalent of 16.11×10^9 GWh.

Regarding wind energy resources, the website 'Ramblings of a Bush Philosopher' has estimated that if the best wind resources of Australia were developed, at least 90 GW of wind power would be possible (Ramblingsdc, 2018).

3) Hydrogen policy

Australia is committed to a technological-neutral policy and regulatory framework that supports new energy sources and enables market innovation and uptake of transformative technology, including hydrogen, which has been noted as a significant opportunity as a transport fuel and for export (Dewar, 2018).

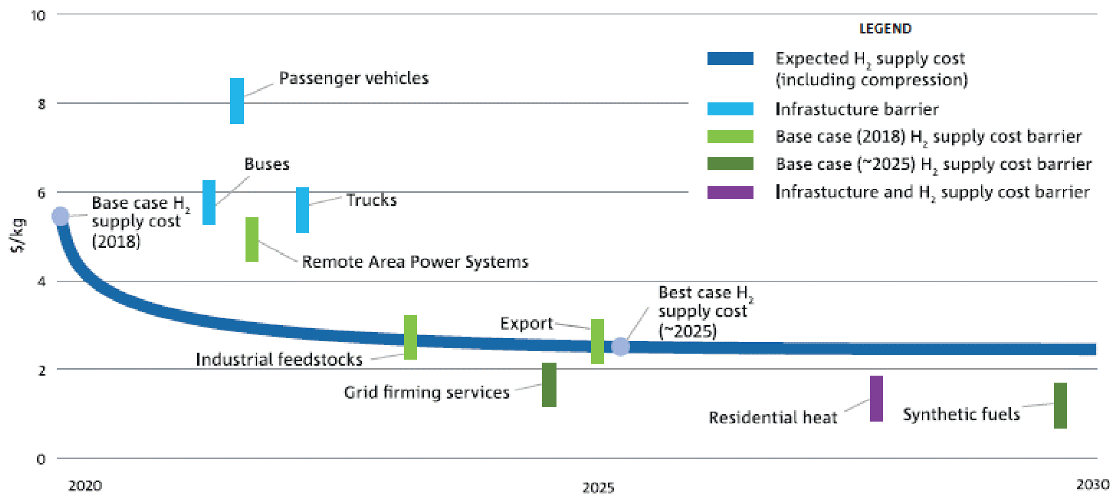
The Australian Energy Council released a plan on 19 December 2018 for a dedicated Working Group that will have six work streams: hydrogen exports; hydrogen for transport; hydrogen in the gas network; hydrogen for industrial users; hydrogen to support electricity systems; and cross-cutting issues. Key priorities for the Working Group include developing a national hydrogen strategy for 2020–2030, and a coordinated approach to projects and programmes that support industry development (Council of Australian Governments, 2018).

The federal government has also issued three reports related to hydrogen:

- 'Hydrogen for Australia's Future' by the Hydrogen Strategy Group
- 'National Hydrogen Roadmap' by Commonwealth Scientific and Industrial Research Organisation (CSIRO, 2018)
- 'Australia's Opportunities from Hydrogen Exports' by Australian Renewable Energy Agency

Especially, the National Hydrogen Roadmap projects the production cost of hydrogen further down the road, as shown in Figure 2.19. The cost of hydrogen from both types of electrolysis, i.e., thermochemical and electrochemical, can be significantly reduced via the scaling of plant capacities (e.g., from 1 MW to 100 MW), greater utilisation, and favourable contracts for low emissions electricity. With several demonstration projects needed to de-risk these assets at scale over the next 3–4 years, it is expected that costs could reach approximately A$2.29–2.79/kg by 2025.

Figure 2.19 Hydrogen Competitiveness in Targeted Applications



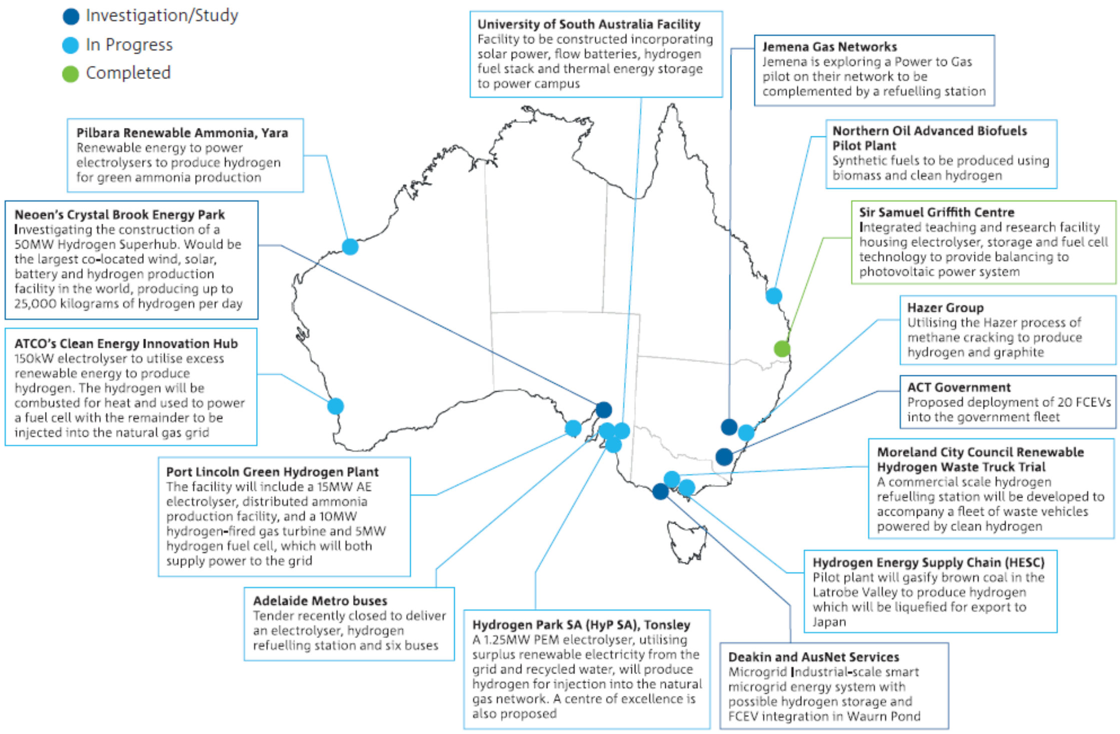
Source: Commonwealth Scientific and Industrial Research Organisation; National Hydrogen Roadmap.

Besides the national strategy, the state of South Australia also drafted ‘A Hydrogen Roadmap for South Australia’ in September 2017 (Government of South Australia, 2017).

Regarding international efforts, Japan’s Kawasaki Heavy Industries has teamed up with the Australian government to lead a A$500 million project to turn coal into liquid hydrogen, in what it has described as one of the world’s first attempts to commercialise the technology. The pilot project aims to generate green energy for use in cars, electricity generation, and industry in Japan from brown coal, one of the dirtiest fuels. This involves converting coal to hydrogen at a power plant in the Latrobe Valley, a region in Australia with some of the world’s most abundant supplies of lignite (Smyth, 2018).

Other hydrogen demonstration projects are also underway, including business-driven projects, as shown in Figure 2.20. For instance, a natural gas powerhouse, ATCO, is about to launch the production, storage, and use of renewable hydrogen to energise a commercial-scale microgrid, testing the use of hydrogen in different settings and applications, including in household appliances, at Jandakot, Western Australia (ARENA, 2018). Renewable energy developer Neoen will start the world’s largest solar- and wind-powered hydrogen hub in South Australia. With a 125 MW windfarm, a 150 MW solar farm, and a 130 MW lithium ion battery, its facility will produce 50 MW hydrogen.

Figure 2.20 Hydrogen Demonstration Projects and Activities in Australia



Source: Commonwealth Scientific and Industrial Research Organisation; National Hydrogen Roadmap.

2.2 China

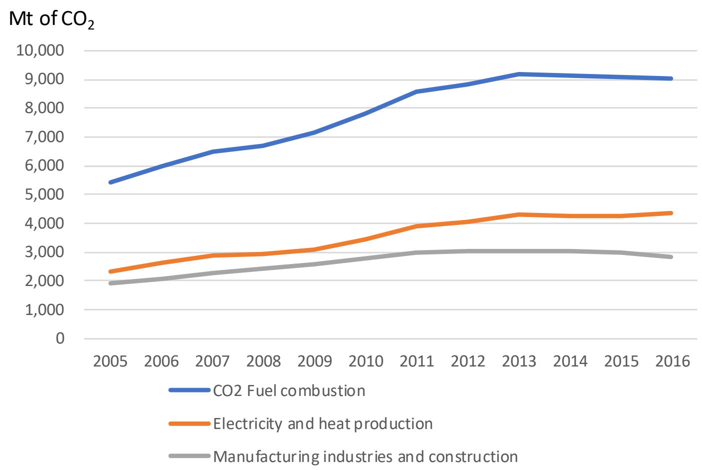
2.2.1 Climate policy, INDC

China has determined its national climate policy goals as follows:

- To achieve the peaking of carbon dioxide emissions around 2030 and making best efforts to peak early;
- To lower carbon dioxide emissions per unit of GDP by 60% to 65% from the 2005 level; and
- To increase the share of non-fossil fuels in primary energy consumption to around 20%.

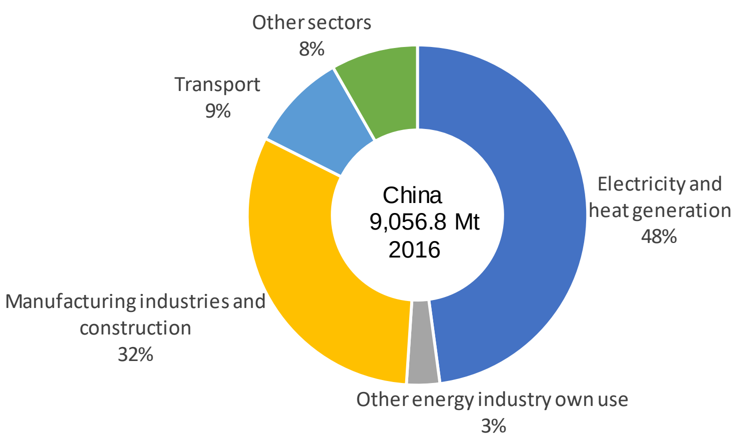
As shown in Figure 2.21, China's CO_2 emissions have plateaued for the last several years. As shown in Figure 2.22, electricity and heat production accounts for 48%, followed by manufacturing, industries and construction for another 32% (UNFCCC, 2015).

Figure 2.21 CO_2 Emissions from Fuel Combustion (2005–2016)



Source: International Energy Agency, CO_2 Emissions from Fuel Combustion 2018.

Figure 2.22 CO_2 Emissions by Sector (2016)



Source: International Energy Agency, CO_2 Emissions from Fuel Combustion 2018.

2.2.2 Renewable energy and hydrogen policy

1) Renewable energy policy

According to China's 13th Five-Year Plan for renewable energy, the National Energy Administration and the state-run Energy Research Society have announced the country's energy prospects. Table 2.7 shows its installed prospects of renewables toward 2030.

Table 2.7 Development Plan for Renewables (in GW)

	2015	**2020**	**2030**
Hydro	320	380	450
Wind power	131	290	450
Solar power/heat	43	160	350
biomass	10	12	50
Total	**504**	**842**	**1,300**

Source: The 13th Five-Year Plan for renewables.

2) Potential of renewable energy

The National Energy Administration released a mid- and-long term development plan for renewables in August 2007. According to the plan, the country gets a solar radiation of 5,000 MJ/m^2/year, and two-thirds of its land could be developed. Regarding wind potential, the plan estimates 300 GW for on-shore and 700 GW for off-shore (NEA, 2007).

3) Hydrogen policy

China has released its Energy Technology Revolution & Innovation Initiative (2016–2030), which sets main 15 targets, including hydrogen (XTECH, 2017; NDRC, 2016). The outline concerning hydrogen is as follows:

(a) Priority fields

(1) The country develops core technologies related to mass production of hydrogen and storage materials, transportation, and hydrogen stations. Specifically, it promotes hydrogen production technology via renewable energy and nuclear power, coal evaporation, reforming methane, and oxidising. It also studies the standardisation and application of storage and filling technologies at hydrogen stations.

(2) The country develops a proton exchange membrane fuel cell (PEMFC) technology, a methane fuel cell (MFC), a solid oxide fuel cell (SOFC), a metal air battery (MeAFC), and other technologies. It promotes the model operation of electric vehicles equipped with PEMFCs and MFCs, and the integrated design of PEMFCs and SOFCs.

(b) Numerical targets, as shown in Table 2.8.

(1) In 2020, the constant output of the PEMFC power system is 50–100 kW, the output weight ratio of the system is 300 Wh/kg or more, the output capacity ratio reaches 3,000 W/L or

more and the lifespan reaches 5,000 hours or more. The fixed amount output of the MFC power supply system is 5–10 kW, the output weight ratio of the system is 345 Wh/kg or more and the lifespan reaches 3,000 hours or more. Hydrogen storage technology with capacity higher than 5% and long-distance, large-volume transportation is realised.

(2) In 2030, the lifespan of the PEMFC's discrete power system is over 10,000 hours, that of the MFC discrete power system is over 40,000 hours and that of the MeAFC discrete power system is over 10,000 hours.

(3) By 2050, the country will deliver the goals of diffusion and application of hydrogen energy and fuel cells.

Table 2.8 Roadmap for Hydrogen Development[3]

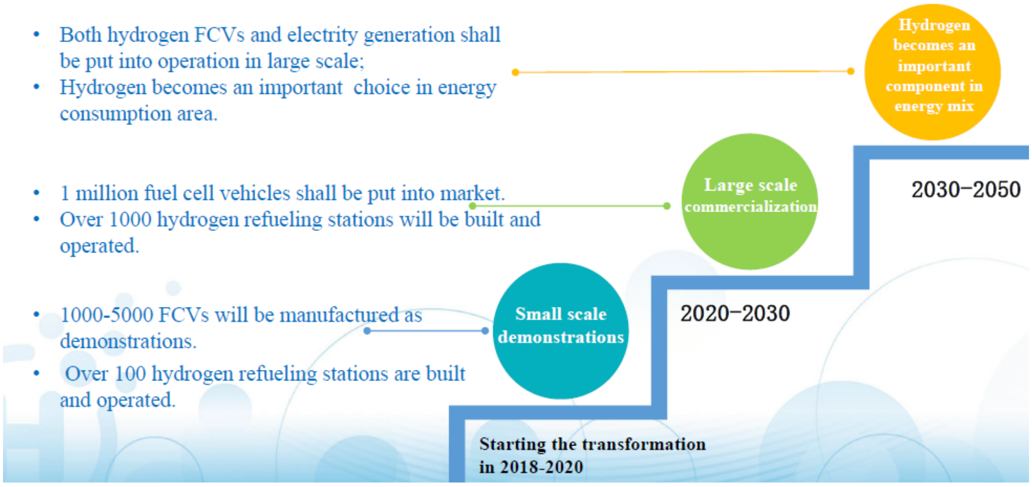
	2016	**2020**	**2030**	**2050**
Hydrogen production capacity (billion cubic meter/year)	70	72	100	-
Hydrogen filling station (unit)	4	100	1,000 or more	-
Fuel cell power plant capacity (MW)	-	200	100,000	-
Fuel cell vehicle (thousand unit)	-	10	2,000	10,000

Source: China National Institute of Standardization.

In February 2018, an interdisciplinary, cross-industry, interagency national alliance, the National Alliance of Hydrogen and Fuel Cell, was founded in Beijing to promote hydrogen (Zhang and Xue, 2018). The alliance is fully committed to developing China's hydrogen industry. At the world's first Hydrogen Energy Ministerial Meeting in Tokyo on October 2018, the Chairman of the China Hydrogen Alliance outlined the targets for China's hydrogen infrastructure, as shown in Figure 2.23.

[3] http://www.china-hydrogen.org/hydrogen/mix/2016-11-08/5718.html (accessed November 2018).

Figure 2.23 Development Target of China's Hydrogen Infrastructure



FCVs = fuel cell vehicles.

Source: Status and Outlook on China's Hydrogen Energy, October 2018 (Wen, 2018).

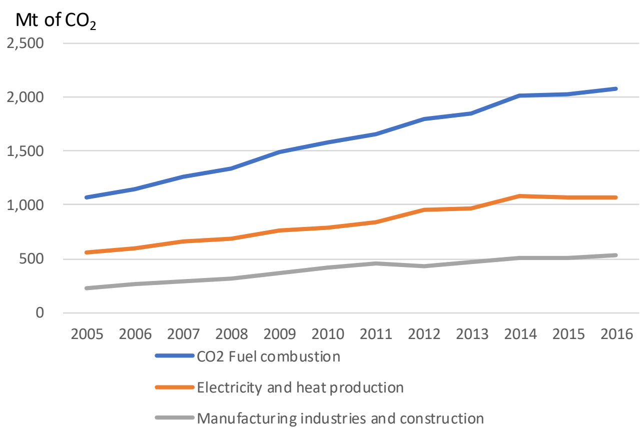
2.3 India

2.3.1 Climate policy, INDC

India intends to reduce the emissions intensity of its GDP by 33%–35% by 2030 from 2005 levels. It also aims to achieve 40% cumulative electric power installed capacity from non-fossil fuel-based energy sources by 2030, with the help of transfer of technology and low-cost international finance, including the Green Climate Fund.

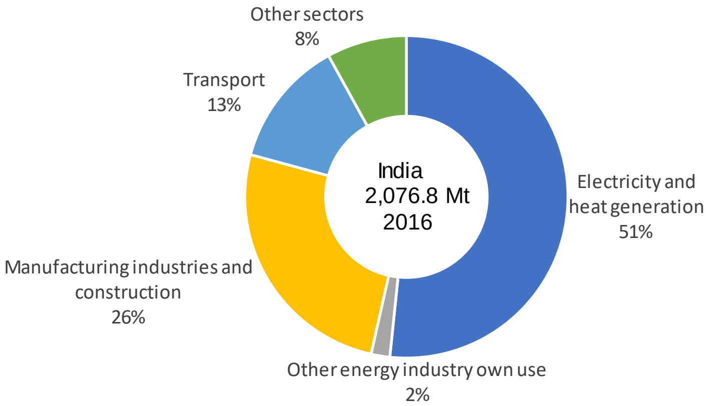
As shown in Figures 2.24 and 2.25, CO_2 emissions have nearly doubled from 2005 to 2016, with electricity and heat production accounting for 51%, followed by manufacturing, industries and construction for another 26% (UNFCCC, 2015).

Figure 2.24 CO_2 Emissions from Fuel Combustion (2005–2016)



Source: International Energy Agency, CO_2 Emissions from Fuel Combustion 2018.

Figure 2.25 CO_2 Emissions by Sector (2016)



Source: International Energy Agency, CO_2 Emissions from Fuel Combustion 2018.

2.3.2 Renewable energy and hydrogen policy

1) Renewable energy policy

Power and Renewables Minister Raj Kumar Singh said in June 2018 that India will add 227 GW of renewable energy capacity by March 2022, which overrides the previous target of 175 GW by 52 GW (Saluja, 2018). Beyond 2022, India is going to leave its future growth market-driven, which is meant to ensure smooth integration (capacity growth will be market-driven without any targeting) (NITI Aayog, Government of India, 2017a).

To hasten streamlining renewables, New and Renewable Energy Secretary Anand Kumar said 30 June 2018 that the country would auction 40 GW of renewable energy projects comprising 30 GW solar and 10 GW wind every year for the next 10 years till 2028 (Economic Times 2018).

The National Institution for Transforming India (NITI Aayog), Government of India, formulated its ‘Draft National Energy Policy’ in June 2017 (NITI Aayog, Government of India, 2017b). NITI Aayog is going to present the policy to Prime Minister in 2019 (Abdi, 2018).

Table 2.9 Electricity Capacity Forecast in Draft National Energy Policy

GW	2012	2022		2040	
		BAU	Ambitious	BAU	Ambitious
Gas Power Stations	24	34	39	46	70
Coal power stations	125	266	251	441	330
Carbon Capture Storage (CCS)	0	1	1	26	26
Nuclear power	5	12	12	23	34
Hydro Power Generation	41	61	61	71	92
Solar PV	1	59	59	237	275
Solar CSP	0	4	5	28	48
Onshore Wind	17	62	62	168	181
Offshore Wind	0	2	2	19	29
Distributed Solar PV	0	36	36	102	120
Other Renewable Sources	8	18	20	43	56
Total	221	555	548	1204	1261

CSP = concentrated solar power, PV = photovoltaics.
Source: NITI Aayog, Draft National Energy Policy.

2) Potential of solar and wind energy

According to the Ministry of Energy, Trade, and Industry's Energy Environmental Strategy Research Report in 2016, India has 753 GW of solar potential throughout the country (METI, 2017b). In terms of wind energy resources, the Ministry of New and Renewable Energy (MNRE) estimates that wind power potential at 100 m above ground level is 302 GW (Jethani, 2016).

3) Hydrogen policy

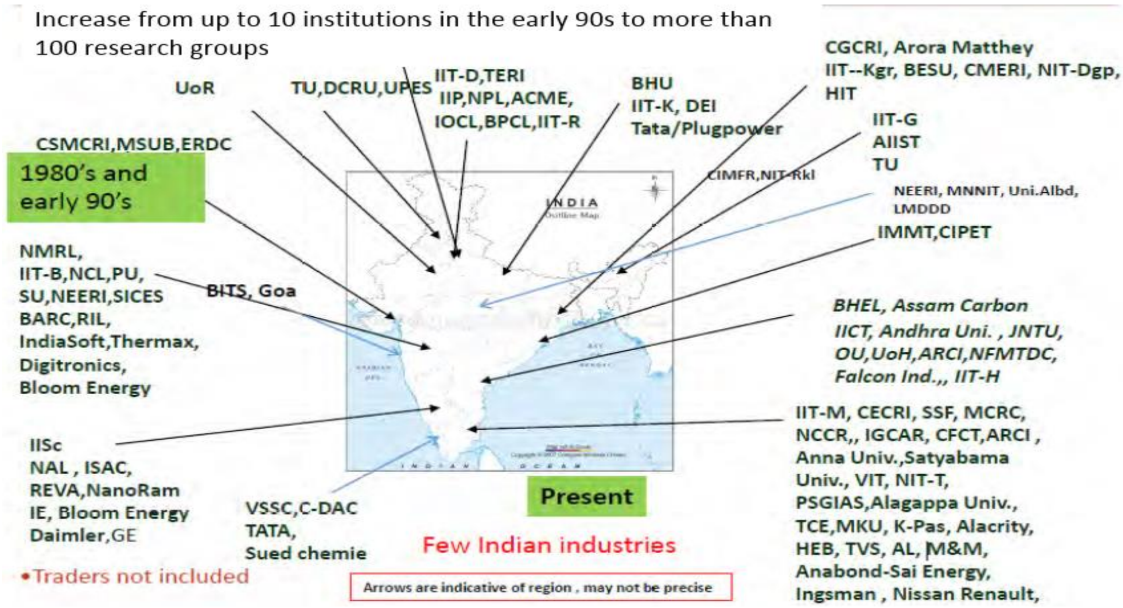
MNRE supports Research, Development and Demonstration, with up to 100% funding to academic and research institutions and up to 50% to industry. Favourable import duties have been introduced for fuel cell systems to be deployed with renewable-generated fuels. Focus areas of the ministry's Research, Development and Demonstration are as follows:

- Hydrogen production from renewable routes;
- Development of materials and techniques for safe storage of hydrogen;
- Research on different types of fuel cells, including materials, components, sub-systems;
- Demonstrations for stationary power generation and transportation; and
- Support development of hydrogen energy infrastructure in the country (Maithani, 2018).

In June 2016, technical reports related to hydrogen and fuel cells have been submitted to a steering committee as the result of studies by experts under the auspices of the Indian government.

As of December 2018, over 100 organisations are working on hydrogen-related research, development, and demonstration across the country, as shown in Figure 2.26. Detailed ongoing projects are shown on the MNRE website (MNRE, 2018).

Figure 2.26 Major Hydrogen and Fuel Cell Activities in India



Source: ARCI International Advanced Research Center.[4]

In terms of international cooperation, at the 9th meeting of the Japan-India Energy Dialogue on May 2018, both governments committed to cooperating on hydrogen utilisation (Seko and Singh, 2018).

2.4 Japan

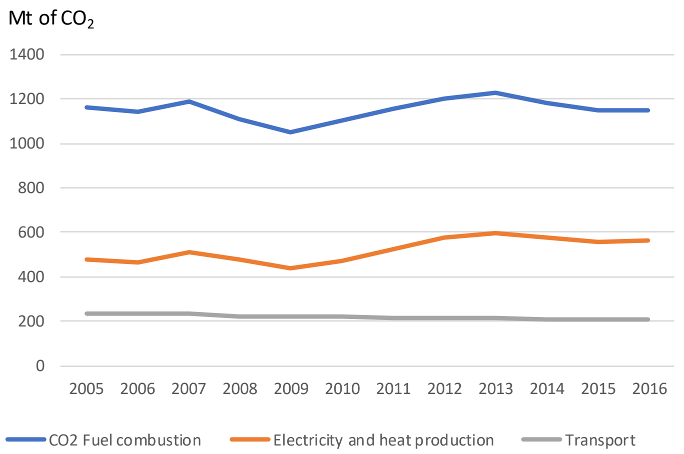
2.4.1 Climate policy, INDC

Japan's goals for reducing greenhouse gas emissions are at the level of 26% by fiscal year 2030, compared to fiscal year 2013.

As shown in Figure 2.27, Japan's CO_2 emissions have been on the decline since 2013. As shown in Figure 2.28, electricity and heat production accounts for 49%, followed by transport for another 18% in 2016.

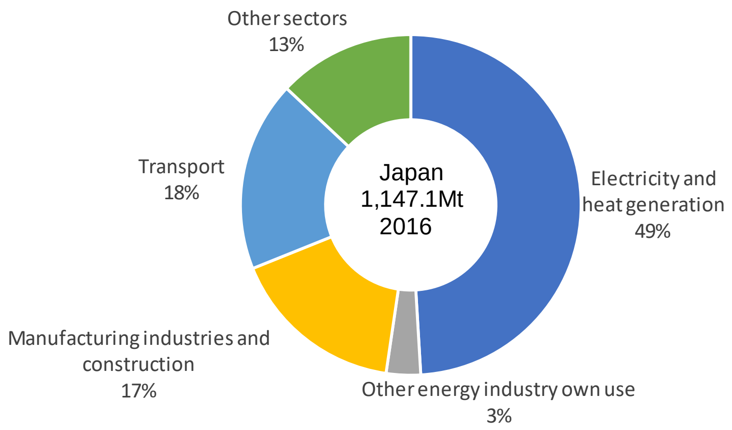
[4] The 4th meeting of hydrogen potential, 10 January 2019.

Figure 2.27 CO_2 Emissions from Fuel Combustion (2005–2016)



Source: International Energy Agency, CO_2 Emissions from Fuel Combustion 2018.

Figure 2.28 CO_2 Emissions by Sector (2016)



Source: International Energy Agency, CO_2 Emissions from Fuel Combustion 2018.

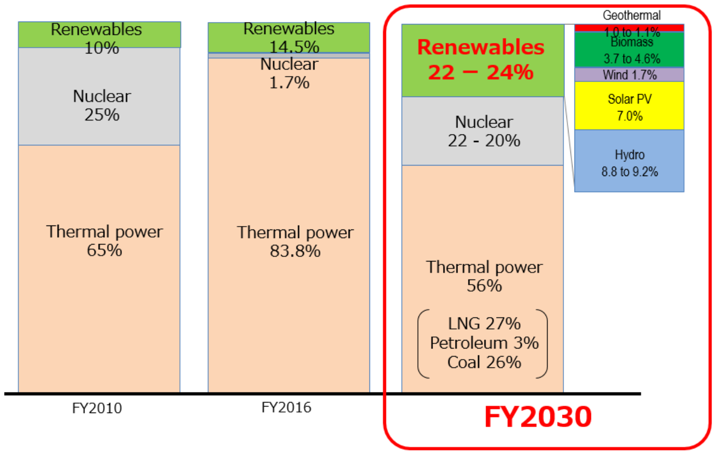
2.5.2 Renewable energy and hydrogen policy

1) Renewable energy policy

Japan's government formulated the 'New Strategic Energy Plan' under the Basic Act on Energy Policy. The plan is based on fundamental principles, namely, 'safety', 'energy security', 'improvement of economic efficiency' and 'environmental suitability'. The latest revision was approved by the cabinet on July 2018 (METI, 2018).

As shown in Figure 2.29, the plan indicates the generation mix target in 2030, when renewables will account for 22%–24% of the total generation. The breakdown of the renewables is shown in Figure 2.30.

Figure 2.29 Generation Mix Target in 2030



FY = fiscal year, LNG = liquefied natural gas, PV = photovoltaic.
Source: Ministry of Energy, Trade, and Industry; the New Strategic Energy Plan.

Figure 2.30 Renewables Introduction toward 2030 Target

	Before FIT (June 2012)	After FIT [A] (as of Sep 2017)	Target [B] (FY2030)	Progress [A]/[B]
Geothermal	0.5GW	0.5GW	1.4 - 1.6GW	33%
Biomass	2.3GW	3.5GW	6.0 - 7.3GW	53%
Wind	2.6GW	3.4GW	10GW	34%
Solar PV	5.6GW	42.4GW	64GW	66%
Hydro	48.1GW	48.4GW	48.5 - 49.3GW	99%

FIT = feed-in tariff, FY = fiscal year, PV = photovoltaic.
Source: Ministry of Energy, Trade, and Industry; the New Strategic Energy Plan.

2) Potential of solar and wind energy

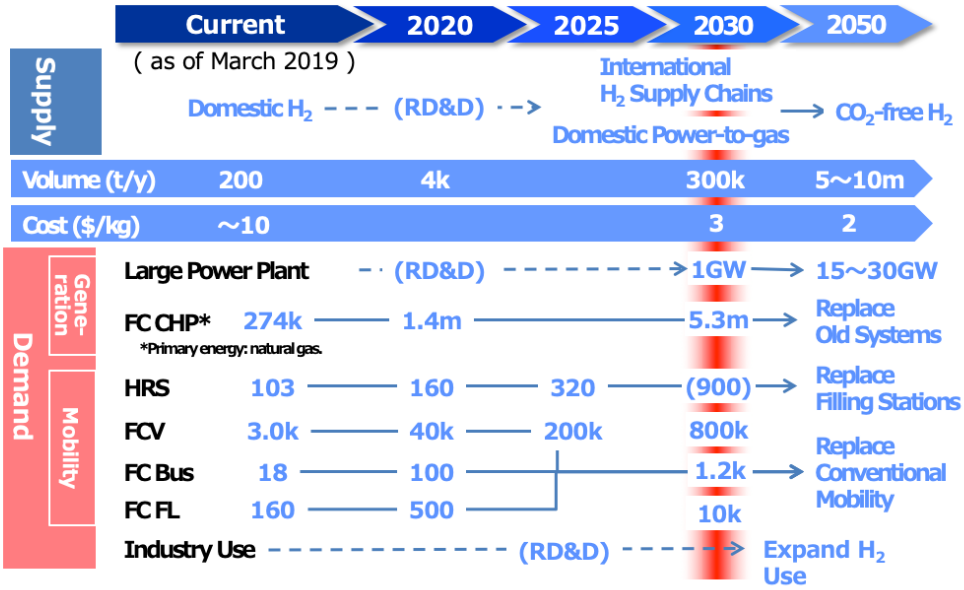
The Ministry of the Environment in Japan calculated that solar potential is 360 GW, and the wind potential, including both on-shore and off-shore, is 1,679 GW (ENV, 2018).

3) Hydrogen policy

On December 2017, Japan released its 'Basic Hydrogen Strategy' (METI, 2017a), which shows future visions that Japan should achieve with an eye on 2050, and also serves as an action plan to accomplish them by 2030. The strategy sets a goal that Japan should reduce hydrogen costs to the same level of conventional energy and provides integrated policies across ministries ranging from hydrogen production to utilisation under the common goals.

Through achieving a carbon-free society under the strategy, Japan will present hydrogen to the rest of the world as a new energy choice and will lead global efforts for establishing a carbon-free society taking advantage of Japan's strong points. The country's hydrogen strategy is shown in Figure 2.31.

Figure 2.31 Japan's Long-Term Scenario for Hydrogen



CHP = combined heat and power, FC = fuel cell, HRS = hydrogen refuelling station, FCV = fuel cell vehicle, FL = forklift.
Source: Ministry of Energy, Trade, and Industry (updated in April 2019).

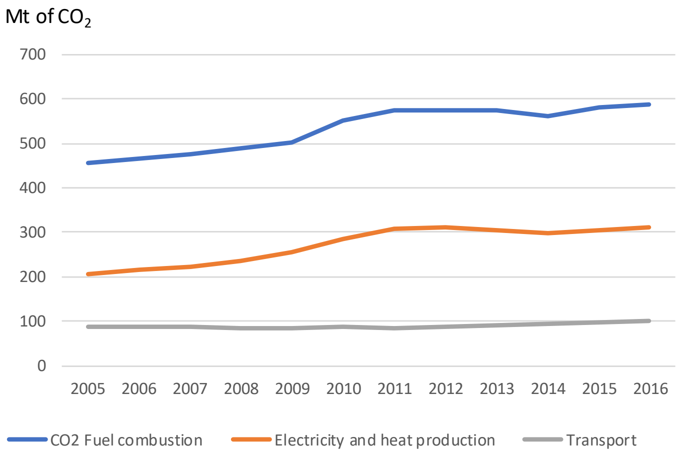
2.5 Korea

2.5.1 Climate Policy, INDC

Korea intends to reduce its greenhouse gas emissions by 37% from its baseline level by 2030.

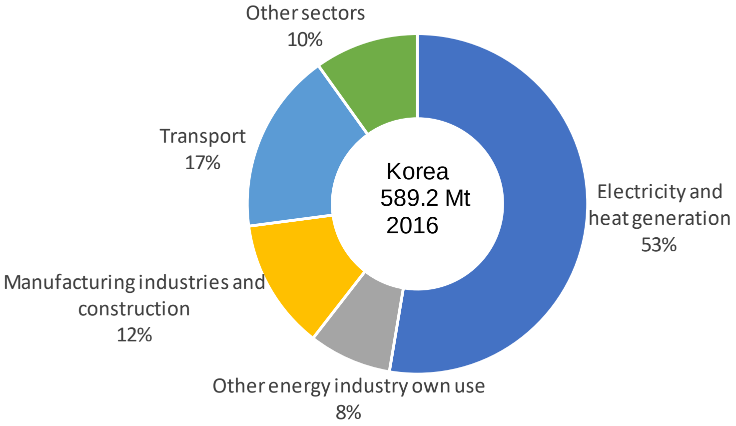
As shown in Figure 2.32, CO_2 emissions have been on the rise, having increased nearly 30% from 2005 to 2016. As shown in Figure 2.33, electricity and heat production accounts for 53%, followed by transport for another 17% in 2016 (UNFCCC, 2015).

Figure 2.32 CO_2 Emissions from Fuel Combustion (2005–2016)



Source: International Energy Agency, CO_2 Emissions from Fuel Combustion 2018.

Figure 2.33 CO_2 Emissions by Sector (2016)



Source: International Energy Agency, CO_2 Emissions from Fuel Combustion 2018.

2.5.2 Renewable energy and hydrogen policy

1) Renewable energy policy

Korea has launched energy transition 'RE 2030', aiming to produce 20% of its power from renewable sources by 2030. As shown in Figure 2.34, Korea will increase renewable energy's share of the energy mix from its current level of 7% in 2017 to 20% by 2030 by providing 48.7 GW in new generation capacity.

To achieve this, Korea intends to expand solar panels for personal use in rural areas and by small business operators by 19.9 GW, which would represent 40% of new capacity. The remaining 28.8 GW will be supplied by large-scale projects at the six public generating companies.

Figure 2.34 Renewable Energy 3020 Goals for Provision of Facilities

Source: Republic of Korea's Ministry of Trade, Industry and Energy.

2) Potential of solar and wind energy

According to the New and Renewable Energy White Paper 2016, the highest technological potential of Korea's solar power is 7,451 GW, and the wind potential is estimated at 63.5 GW for onshore, and 33.2 GW for offshore.

3) Hydrogen policy

Korea released 'Industrial Innovation 2020 Platform' in June 2018. In the platform, the government and the private sector decided to invest W2.6 trillion by 2020 to build a car industry ecosystem and stay ahead of the global market. Korea plans to expand hydrogen production plants and establish package-type hydrogen filling stations to supply 16,000 hydrogen vehicles by 2022, as shown in Table 2.10.

Table 2.10 Investment Plan for Hydrogen Vehicles

	2018	2019	2020–2022
Amount of investment	190 billion won	420 billion won	2 trillion won
Major projects	- Establishment of private-driven special purpose company for hydrogen vehicle	- Production of prototype hydrogen bus - Commercialised hydrogen storage facilities for buses - Mass production of local CNG	- Expansion of factories that produce hydrogen vehicles - Expansion of factories that produce fuel cell stacks - Mass production of package-type fuel charging stations

CNG = compressed natural gas.
Source: Ministry of Trade, Industry, and Energy, Industrial Innovation 2020.

Furthermore, in January 2019, the government announced a hydrogen economy roadmap (see Table 2.11 for an outline). The plan is focused on increasing production of hydrogen-powered fuel cell vehicles, expanding the supply of fuel cells, and building systems for producing and supplying hydrogen. By 2040, the plan seeks to increase the cumulative total of fuel cell vehicles to 6.2 million, raise the number of hydrogen refuelling stations to 1,200, and boost the supply of power-generating fuel cells. Through these measures, the government hopes to create 420,000 jobs and W43 trillion in value added each year by 2040 (Hankyoreh, 2019; FuelCellsWorks, 2019).

Table 2.11 Outline of Hydrogen Roadmap

Field	Content
Hydrogen Buses	- Thirty-five buses are to be rolled out in 2019. - This number will be ramped up to 2,000 by 2022 and to 41,000 by 2040.
Hydrogen Trucks	- From 2021, the public sector will convert garbage collection trucks and sweepers into hydrogen trucks and gradually spread this to the private sector such as logistics trucks and vans.
Energy	- Supply 15 GW of fuel cell for power generation by 2040. ▶ Development of fuel cells: 307.6 MW (2018 years) → 1.5 GW (domestic 1 GW, 2022) → 15 GW (2040) ▶ Supply of 2.1 GW (940,000 households) from fuel cells for homes and buildings by 2040
Hydrogen Production	- By 2040, the annual supply of hydrogen will reach 5,260,000 tonnes, and the price per kg will reach 3,000 won. ▶ Use about 50,000 tonnes (250,000 hydrogen vehicles). ▶ Overseas production: Establish overseas production base to stabilise hydrogen production, imports, supply and demand
Legal basis for hydrogen economy support	- In 2019, the Hydrogen Economy Act (tentative name) will be enacted to establish a basic plan for the implementation of the hydrogen economy, and a legal basis for the hydrogen economy will be established.

Source: Ministry of Trade, Industry, and Energy, Hydrogen roadmap (Park, 2016).

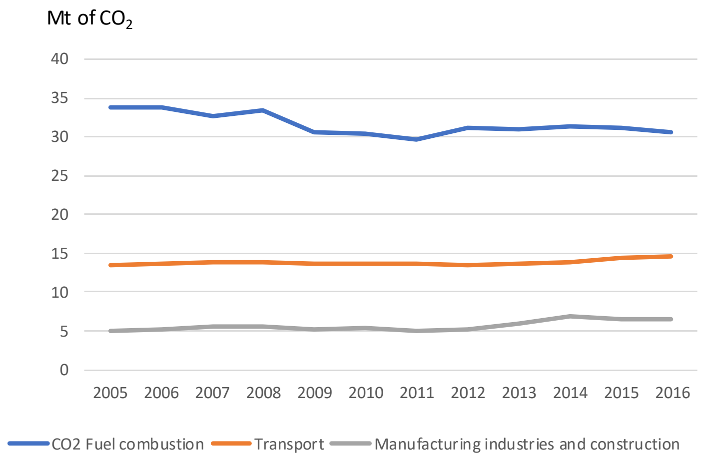
2.6 New Zealand

2.6.1 Climate policy, INDC

New Zealand has committed to reducing greenhouse gas emissions to 30% below 2005 levels by 2030.

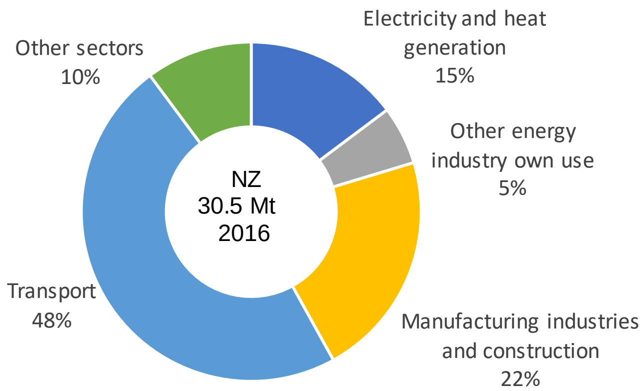
As shown in Figure 2.35, CO_2 emissions have been decreasing since 2005, and have remained unchanged for the last several years. As shown in Figure 2.36, transport accounted for 48%, followed by manufacturing, industries, and construction for another 22% (UNFCCC, 2015).

Figure 2.35 CO_2 Emissions from Fuel Combustion (2005–2016)



Source: International Energy Agency, CO_2 Emissions from Fuel Combustion 2018.

Figure 2.36 CO_2 Emissions by Sector (2016)



NZ = New Zealand.
Source: International Energy Agency, CO_2 Emissions from Fuel Combustion 2018.

2.6.2 Renewable energy and hydrogen policy

1) Renewable energy policy

Building on New Zealand's 2011 'Energy Strategy 2011-2021', the country's prime minister, Jacinda Ardern, launched a new plan on November 2017 that aims for 100% renewable electricity generation by 2035, and carbon neutrality by 2050 (Jones, 2017).

2) Potential of solar and wind generation

Solar power generation is currently a small proportion of New Zealand's energy supply. Price reductions for solar photovoltaic equipment have made it more popular with homeowners and businesses, despite its remaining costlier than grid-supplied electricity (EECA, 2016). According to the Energy Efficiency and Conservation Authority, New Zealand's solar energy resource is about 4 kWh/m^2 (Eltayeb, 2013).

Regarding wind potential, New Zealand is exposed to winds travelling across the ocean uninterrupted by other land forms. A steady succession of troughs and depressions passes to the east of the country, creating the predominantly westerly wind flow (Windenergy, 2018). According to a report, 'Renewable Energy Potential in New Zealand' by Massey University, an upper limit of the available onshore wind resource is approximately 127,370 GWh/year (Eltayeb, 2013).

3) Hydrogen policy

The government is developing transition plan toward decarbonisation that will launch in 2019. To promote hydrogen, New Zealand signed a Memorandum of Cooperation with Japan in October 2018 (Seko and Woods, 2018). In the agreement, both countries are set to cooperate on a strategic road map for New Zealand to develop and expand the demand of hydrogen in the country.

New offshore oil and gas development will be prohibited in 2019, and the country needs to shift toward new industries, such as hydrogen. For automotive fuel, New Zealand promotes biofuel and electrical vehicles and considered introducing fuel cell vehicles for reduction of gasoline and diesel consumption.

Regarding reports related to hydrogen, Hiringa Energy, New Plymouth District Council, and its partners published 'Energy Future Action Plan for Taranaki' on March 2018, including establishment of a hydrogen-based energy ecosystem 'H2 Taranaki' (Hiringa, 2019).

A new venture to investigate hydrogen production using geothermal energy is also underway. For instance, Taupo-based Tuaropali Trust and Japan's construction company, Obayashi Corporation, have signed an MOU for a project to pilot the commercial production of hydrogen on 14 February 2018 (Obayashi, 2019), starting with the construction of a plant in December 2018.

With regard to business-oriented efforts, Ports of Auckland unveiled in December 2018 that it will build a hydrogen production and refuelling facility at its Waitematā port. The company, and project partners Auckland Council, Auckland Transport, and KiwiRail, will invest in hydrogen fuel cell vehicles, including port equipment, buses, and cars as part of the project. They have set an ambitious target to be a zero-emissions port by 2040. Demonstration vehicles will be able to fill up with hydrogen at the facility, which will be just like filling up a car with CNG or LPG (Ports of Auckland, 2018).

Table 2.12 Organisations in Charge of Hydrogen Policy

Area	Country	Ministry, Department, or Organization
ASEAN	Brunei Darussalam	Energy Department, Prime Minister’s office
	Indonesia	Ministry of Energy and Mineral Resources (MEMR)
	Malaysia	Ministry of Energy, Science, Technology, Environment and Climate Change (MESTECC) Sustainable Energy Development Authority (SEDA)
	Philippines	Department of Energy (DOE)
	Singapore	Ministry of Trade and Industry (MTI)
	Thailand	Ministry of Energy (MOE) Department of Alternative Energy Development and Efficiency (DEDE)
	Viet Nam	Ministry of Industry and Trade (MOIT)
EAS	Australia	Department of Industry, Innovation and Science Australian Renewable Energy Agency (ARENA)
	China	National Energy Administration (NEA) National Alliance of Hydrogen and Fuel Cell
	India	Ministry of New and Renewable Energy (MNRE)
	Japan	Ministry of Economy, Trade and Industry (METI)
	Republic of Korea	Ministry of Trade, Industry and Energy (MOTIE)
	New Zealand	Ministry of Business, Innovation and Employment (MBIE)

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Chapter 3

Estimation of Hydrogen Demand Potential in the East Asia Summit Region

This chapter estimates hydrogen's demand potential, as well as its ability to compete with conventional fuels and its CO_2 reduction effect. There are many uncertainties regarding the hydrogen supply chain due to varying promotion policies, utilisation technologies, transportation/distribution logistics, and costs. In addition, there is no conventional study of hydrogen demand, such as the International Energy Agency's (IEA) World Energy Outlook (WEO). For these reasons, this study refers to various available resources, including the Economic Research Institute for ASEAN and East Asia's (ERIA) energy outlook, as well as the latest hydrogen utilisation and technology trends, and other demand estimation documents (these reference materials are described in Appendix 3.1).

This study only estimates hydrogen demand potential for energy use, and does not include its use as a feedstock. Although ammonia is regarded as a hydrogen carrier and its direct combustion has been demonstrated, it is excluded in this study. Furthermore, hydrogen supply through onsite natural gas reforming is also excluded because it can be classified as natural gas demand.

The three demand scenarios projected here are grouped by sector—electricity generation, industry and transport – as shown in Table 3.1:

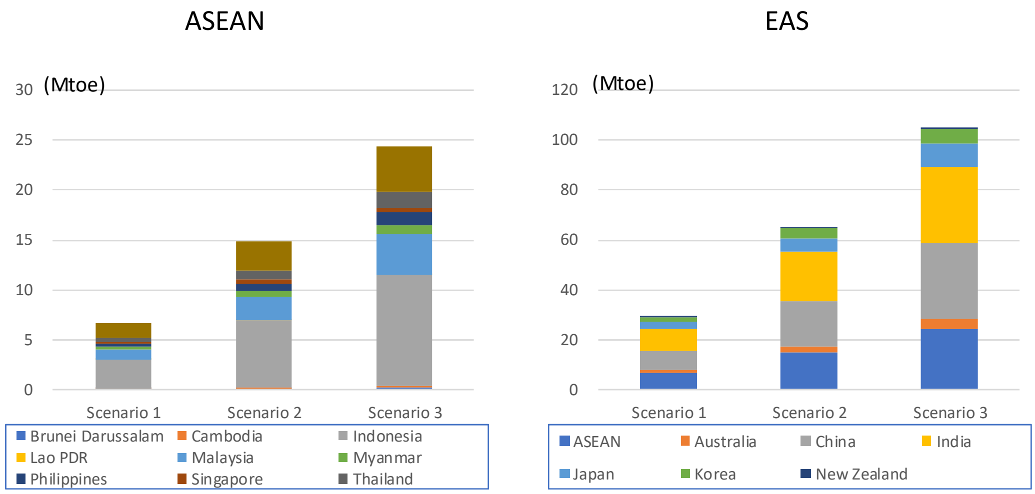
Table 3.1 Summary of Assumptions/Scenarios

Sector	Fuel		Scenario 1	Scenario 2	Scenario 3
Electricity generation	Coal	20% of new coal-fired electricity generation will be converted to natural gas and H_2 mixed fuel-fired generation	H_2 concentration of mixed fuel		
			H_2: 10% Nat. gas: 90%	H_2: 20% Nat. gas: 80%	H_2: 30% Nat. gas: 70%
	Natural gas	20% of new natural gas-fired electricity generation will be converted to natural gas and H_2 mixed fuel-fired generation			
Industry	Natural gas	20% of natural gas consumption for industrial purposes will be replaced by natural gas and H_2 mixed fuel			
Transport	Gasoline	Passenger Fuel Cell Vehicle: Gasoline demand will be converted to H_2	Share of H_2/ gasoline for passenger cars		
			OECD H_2: 2.0% Gasoline: 98% Non-OECD H_2: 1.0% Gasoline: 99%	OECD H_2: 10% Gasoline: 90% Non-OECD H_2: 5% Gasoline: 95%	OECD H_2: 20% Gasoline: 80% Non-OECD H_2: 10% Gasoline: 90%
	Diesel	Fuel Cell Bus: Diesel demand will be converted to H_2	Share of H_2/ diesel for buses		
			Japan H_2: 0.05% Gasoline: 99.95% Other countries H_2: 0.025% Gasoline: 99.975%	Japan H_2: 0.1% Gasoline: 99.9% Other countries H_2: 0.05% Gasoline: 99.95%	Japan H_2: 0.2% Gasoline: 99.8% Other countries H_2: 0.1% Gasoline: 99.9%
	Diesel	Fuel Cell Train: Diesel consumption for rail transport will be converted to H_2	Share of H_2/ diesel for rail transport		
			H_2: 5% Diesel: 95%	H_2: 10% Diesel: 90%	H_2: 20% Diesel: 80%

OECD = Organisation for Economic Co-operation and Development.
Source: Author.

Figure 3.1 further shows that, by 2040, the potential Association of Southeast Asian Nations (ASEAN) hydrogen demand is 6.6 million tonnes of oil equivalent (Mtoe) in Scenario 1, 14.9 Mtoe in Scenario 2, and 24.4 Mtoe in Scenario 3. The potential East Asia Summit (EAS) region demand is 28.9 Mtoe in Scenario 1, 64.9 Mtoe in Scenario 2, and 104.7 Mtoe in Scenario 3. Indonesia has the largest hydrogen demand potential amongst ASEAN member countries, followed by Malaysia and Viet Nam. China has the largest hydrogen demand potential in the EAS region, followed by India and ASEAN total.

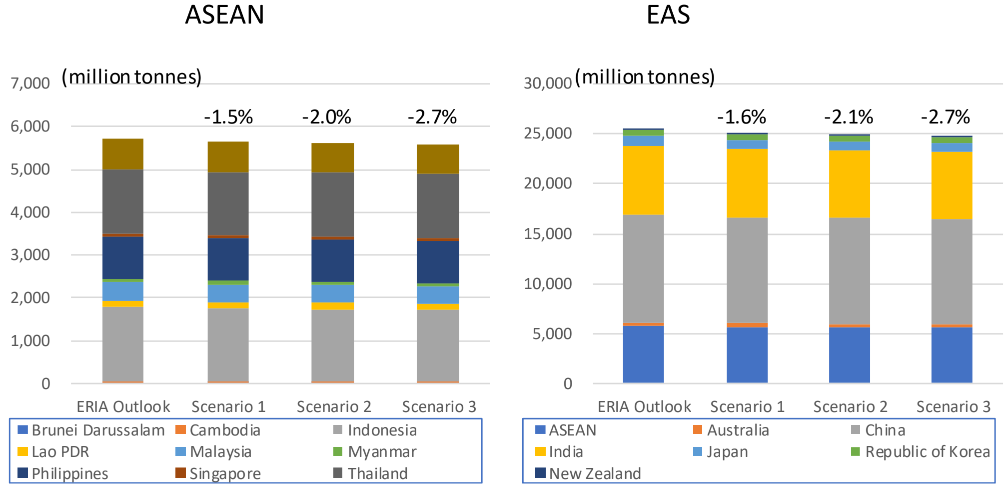
Figure 3.1 Hydrogen Demand Potential in 2040, by Country



ASEAN = Association of Southeast Asian Nations, EAS = East Asia Summit, Lao PDR = Lao People's Democratic Republic, Mtoe = million tonnes of oil equivalent.
Source: Author.

As shown in Figure 3.2, CO_2 emissions can be reduced by up to 2.7% depending on the scenario. Indonesia has the largest CO_2 emissions reduction potential in ASEAN member countries, while India has the largest CO_2 emissions reduction potential, despite being the second-largest EAS CO_2 emitter.

Figure 3.2 Total CO_2 Emissions from Fuel Combustion by Country



ASEAN = Association of Southeast Asian Nations, EAS = East Asia Summit, ERIA = Economic Research Institute of ASEAN and East Asia, Lao PDR = Lao People's Democratic Republic.
Source: Author.

1. Basic Assumptions for Hydrogen Demand Estimation

Although it is difficult to foresee future hydrogen supply chain developments, Table 3.2 shows the study's basic assumptions.

Table 3.2 Basic Assumptions for Estimation of Hydrogen Demand Potential

The national hydrogen pipeline, as well as refuelling stations, will only be partially established in 2040.
Ammonia, which is a hydrogen carrier, is excluded, as well as hydrogen for generating ammonia and/or methanol.[1]
Commercialised hydrogen utilisation technologies in 2040: ● Hydrogen and natural gas mixed fuel gas turbine ● Hydrogen and natural gas mixed fuel large scale boiler ● Passenger fuel cell vehicle ● Fuel cell bus ● Fuel cell train
Technology needing development by 2040: ● Utility scale fuel cell ● Heavy-duty fuel cell vehicle ● Fuel cell ship Technically available, but international and domestic refuelling infrastructures will only be partially established in 2040.

[1] Currently, most ammonia production is for nitrogen fertiliser. If ammonia were to be used for energy, its demand would be one or two times greater than its current level, thus affecting its global supply/demand balance (Institute of Energy Economics, Japan, October 2015).

Note: Distributed fuel cell systems are not included in this study because hydrogen would not be supplied directly without a functioning pipeline. Hydrogen for a distributed fuel cell system would be produced from on-site natural gas reforming, categorising it as part of natural gas demand.

Source: Author.

2. Hydrogen Demand Potential for Electricity Generation

This section assesses the potential demand by 2040 for different scenarios of hydrogen-fired electricity generation under the basic assumption that a mixture of natural gas and hydrogen is used as a generator fuel. Compared to conventional fossil fuels, hydrogen emits lower CO_2, especially when produced from renewable energy. Furthermore, hydrogen combustion emits no particulate matter or sulphur oxide, thus aiding regional environmental and human health.

2.1. Assumptions and Scenario

Table 3.3 shows the assumptions and scenarios to estimate hydrogen demand potential for electricity generation.

Table 3.3 Assumptions and Scenarios of Electricity Generation

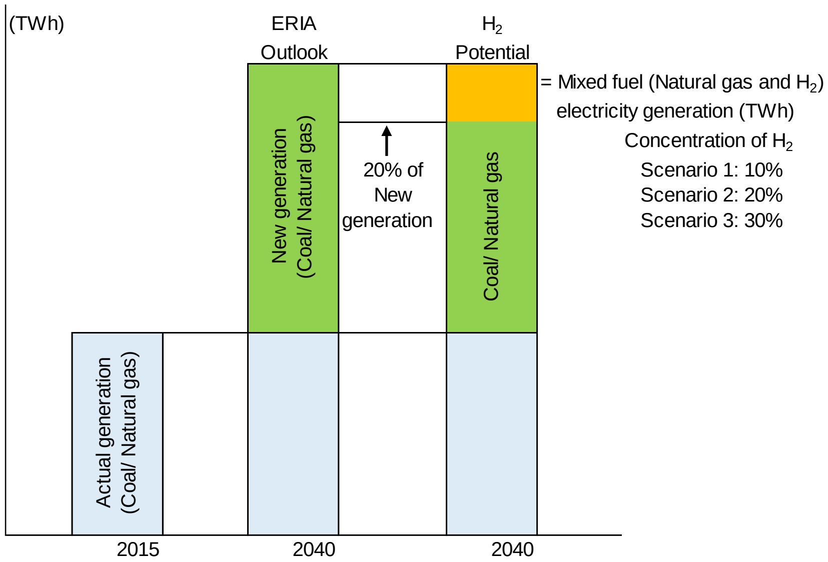
Fuel	Assumed hydrogen use in 2040	Hydrogen concentration in mixed fuel (calorific value basis)
Natural gas	20% of new natural gas-fired electricity generation will be converted to natural gas and hydrogen mixed fuel-fired generation	Concentration Scenario 1: 10% Scenario 2: 20% Scenario 3: 30%
Coal	20% of new coal-fired electricity generation will be converted to natural gas and hydrogen mixed fuel-fired generation	

Source: Author.

Thanks to large recent investments to meet rapidly growing demand, existing fossil-fired power plants in non-Organisation for Economic Co-operation and Development (OECD) countries are relatively young, meaning it is assumed that they will keep operating through 2040. Because of this, the necessary amount of new coal-fired or new natural gas-fired power plants, in terms of energy (kWh), is defined as the difference between electricity demand in 2015 (actual) and 2040 (prospective).

On the other hand, for OECD countries, the age of existing fossil-fired power plants is relatively old due to stagnant or even decreasing electricity demand. Therefore, electricity generation in 2040 is regarded as new. Figure 3.3 outlines the assumptions and scenarios.

Figure 3.3 Outline of Assumptions and Scenarios for Electricity Generation



ERIA = Economic Research Institute of ASEAN and East Asia.
Source: Author.

Based on recent technological developments, hydrogen concentration in a mixed fuel is assumed to be as much as 30%, which MHPS, one of the major utility-scale gas turbine manufacturers, has successfully demonstrated. MHPS's next challenge is developing a pure hydrogen-burning gas turbine. However, considering the reported difficulty of even a 10% increase in the concentration of hydrogen in a mixed fuel, it is safe to assume that a pure hydrogen-burning gas turbine will not be commercialised before 2040. (See Box 3.1.)

10%: 5%–15% concentration is capable with some modification of existing gas turbine technology. (IEA, World Energy Outlook 2017)

20%: Existing gas turbine technology can be applied. (MHPS)

30%: Demonstration succeeded. (MHPS)

Box 3.1 Challenges for Burning Higher Hydrogen-Content Fuel in Gas Turbines

In cases of 20% hydrogen concentration, existing gas turbines can be used; however, 30% hydrogen concentration poses quite a challenge for the gas turbine engineer, due to the following considerations:

- Flashback

  Flashback is a phenomenon where the flames inside the combustor travel up the incoming fuel and leave the chamber. Since hydrogen burns rapidly, flashback commonly occurs.

- NOx

  Fuel and air are mixed prior to entering the combustor. While this enables low-NOx combustion, flashback occurs more frequently when the hydrogen concentration in fuel increases. By securing the required distance, sufficient mixing can be accomplished while also achieving low NOx, but this ends up increasing the flashback risk.

- Combustion pressure fluctuation

  Temperatures inside the combustor reach 1,600 °C, and it is known that imposing an extremely high thermal load on the cylinder results in a very loud noise due to its specified eigenvalue.

Source: MHPS, https://www.mhps.com/special/hydrogen/article_1/index.html

2.2. Hydrogen Demand Potential in Electricity Generation

Table 3.4 shows the assumptions of thermal efficiency and hydrogen specification to calculate hydrogen demand potential.

Table 3.4 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.

Table 3.5 shows the estimated hydrogen demand potential for electricity generation by country in 2040 (the calculation method is described in Appendix 3.2).

Table 3.5 Hydrogen Demand Potential for Electricity Generation by Country in 2040
(in Mtoe)

Country	Scenario 1	Scenario 2	Scenario 3
Brunei Darussalam	0.0	0.1	0.1
Cambodia	0.0	0.1	0.1
Indonesia	1.9	3.9	5.8
Lao PDR	-	-	-
Malaysia	0.6	1.1	1.7
Myanmar	0.1	0.2	0.3
Philippines	0.3	0.6	0.9
Singapore	0.1	0.2	0.3
Thailand	0.2	0.5	0.7
Viet Nam	1.1	2.1	3.2
ASEAN	**4.4**	**8.7**	**13.1**
Australia	0.7	1.4	2.1
China	4.8	9.7	14.5
India	7.4	14.8	22.3
Japan	2.0	4.0	6.0
Republic of Korea	1.5	3.1	4.6
New Zealand	0.0	0.1	0.1
Other than ASEAN	**16.5**	**33.1**	**49.6**
EAS Region Total	**20.9**	**41.8**	**62.7**

ASEAN = Association of Southeast Asian Nations, EAS = East Asia Summit, Lao PDR = Lao People's Democratic Republic, Mtoe = million tonnes of oil equivalent.
Note: Lao PDR has no plan to introduce natural gas; thus, the assumption is that coal will not be replaced by hydrogen and natural gas mixed fuel. Calculation method is shown in Appendixes. The same applies hereafter.
Source: Author.

3. Hydrogen Demand Potential for Heat Demand in Industry

In this section, the potential demand for hydrogen-based heat in industry is estimated.

3.1. Assumption and Scenario

Table 3.6 shows the assumption and scenario of industry's potential hydrogen demand. In general, the estimation method is almost the same as for the electricity generation sector, with industry assumed to consume hydrogen as a natural gas mixture, rather than pure hydrogen, for generating heat.

Table 3.6 Assumption and Scenario of Hydrogen Demand Potential for Industry

Fuel	Assumed hydrogen use in 2040	Hydrogen concentration in mixed fuel (on the basis of calorific value)
Natural gas	- Small-scale natural gas/hydrogen mixed-fuel pipelines will be created in industrial parks located near natural gas/hydrogen mixed-fuel-combusting electricity generation plants. - Natural gas for industrial boilers will be replaced by natural gas/hydrogen mixed fuel in areas near mixed-fuel pipelines. - 20% of natural gas consumption for industrial purposes is assumed to be replaced by natural gas/hydrogen mixed fuel.	Same fuel for electricity generation is used for industrial boilers. Concentration Scenario 1: 10% Scenario 2: 20% Scenario 3: 30%

Source: Author.

3.2. Hydrogen Demand Potential for Heat Demand in Industry

Table 3.7 shows the hydrogen demand potential for industry by country in 2040 (the calculation method is described in Appendix 3.3).

Table 3.7 Hydrogen Demand Potential in Industry Sector in 2040 (in Mtoe)

Country	Scenario 1	Scenario 2	Scenario 3
Brunei Darussalam	-	-	-
Cambodia	-	-	-
Indonesia	0.3	0.5	0.8
Lao PDR	-	-	-
Malaysia	0.3	0.5	0.8
Myanmar	0.0	0.1	0.1
Philippines	0.0	0.0	0.0
Singapore	0.0	0.1	0.1
Thailand	0.2	0.4	0.6
Viet Nam	0.1	0.3	0.4
ASEAN	**0.9**	**1.8**	**2.8**
Australia	0.2	0.3	0.5
China	1.8	3.6	5.4
India	0.7	1.3	2.0
Japan	0.3	0.6	0.9
Republic of Korea	0.2	0.4	0.7
New Zealand	0.0	0.0	0.1
Other than ASEAN	**3.2**	**6.4**	**9.5**
EAS Region Total	**4.1**	**8.2**	**12.3**

ASEAN = Association of Southeast Asian Nations, EAS = East Asia Summit, Lao PDR = Lao People's Democratic Republic, Mtoe = million tonnes of oil equivalent.
Note: Brunei Darussalam, Cambodia, and Lao PDR have no industrial natural gas demand projected for 2040.
Source: Author.

4. Hydrogen Demand Potential for Transport

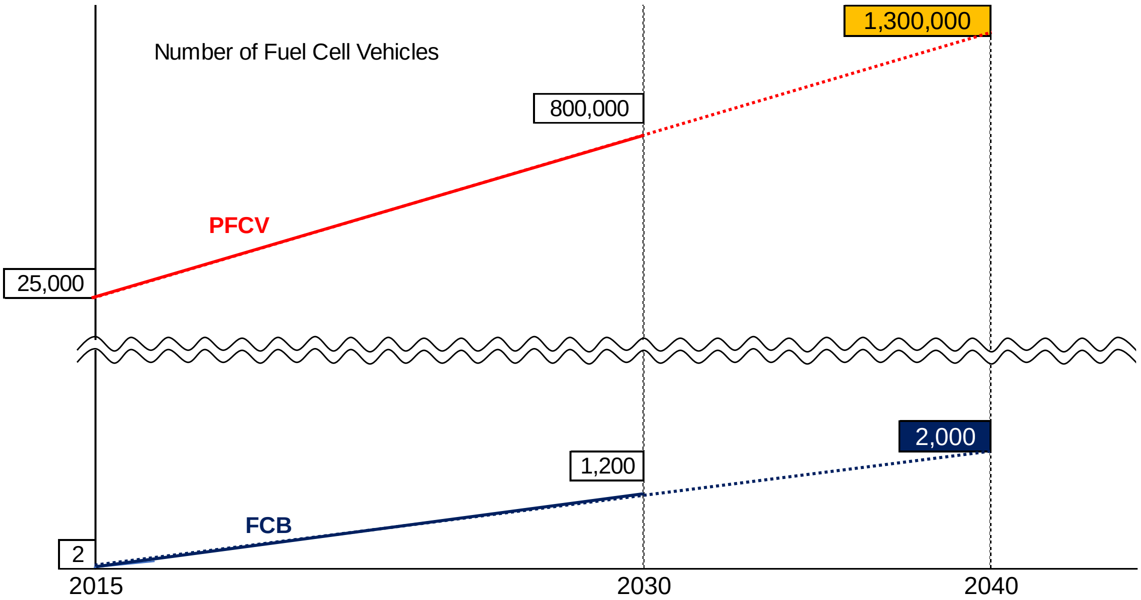
As described in section 3.1, passenger fuel cell vehicles (PFCVs), fuel cell buses (FCBs) and fuel cell trains (FCTs) are studied. For PFCVs and FCBs, Japan's scenario was set first and then applied to OECD countries and non-OECD countries differently.

4.1. Assumption and Scenario for Transport

4.1.1 Number of PFCVs and FCBs in Japan

The study assumed that Japan's Basic Hydrogen Strategy, i.e. 800,000 PFCVs and 1,200 FCBs by 2030, will be accomplished. The numbers of PFCVs and FCBs in 2040 are estimated as a straight-line extrapolation of the trend until 2030, i.e. 1,300,000 and 2,000, respectively, as shown in Figure 3.4.

Figure 3.4 Estimation of Number of PFCVs and FCBs in Japan (2040)



FCB = fuel cell bus, PFCV = passenger fuel cell vehicles.
Source: Author.

4.1.2 PFCV Scenario

First, Japan's PFCV hydrogen demand potential through 2040 is assumed, as shown in Table 3.8. Of all Japan's gasoline-powered passenger vehicles in 2040, 2% are assumed to be converted to hydrogen.[2]

Table 3.8 Basic PFCV Scenario in Japan (2040)

(a)	Number of vehicles in 2040	72 million	ERIA outlook
(b)	Estimated share of passenger vehicles in 2040	79%	same as 2016
(c)	Estimated number of passenger vehicles in 2040	57 million	(a)*(b)
(d)	Number of PFCV in 2040	1.3 million	Figure 3.4
(e)	Estimated share of PFCV in 2040	2%	(d)/(c)

ERIA = Economic Research Institute of ASEAN and East Asia, PFCV = passenger fuel cell vehicles.
Source: Author.

[2] Passenger vehicles are assumed to be gasoline-powered.

Next, other countries' scenarios are assumed, i.e. that OECD countries' PFCV penetration rate will be the same as Japan's, while the rate will be halved in non-OECD countries. Table 3.9 shows the scenarios for the share of PFCV in 2040.

Table 3.9 PFCV Scenarios

Scenario	Japan and other OECD	Non-OECD
Scenario 1	(Japan's basic scenario) 2%	1%
Scenario 2	10%	5%
Scenario 3	20%	10%

OECD = Organisation for Economic Co-operation and Development, PFCV = passenger fuel cell vehicle.
Source: Author.

To calculate PFCV hydrogen demand, the fuel mileage difference between gasoline vehicles and hydrogen vehicles should be considered. For the TOYOTA CROWN (gasoline) and the TOYOTA MIRAI (hydrogen) (see section 3.5.4), the mileage of hydrogen vehicles is 2.7 times better than that of gasoline vehicles;[3] thus, PFCV hydrogen demand is calculated as indicated below:

PFCV hydrogen demand (toe) = Replaced gasoline demand (toe)/2.7

4.1.3 FCB Scenario

First, Japan's FCB hydrogen demand potential is assumed, with Table 3.10 showing its basic 2040 FCB scenario. In Japan, 0.02% of diesel consumption for transport in 2040 is assumed to be converted to hydrogen.

[3] Crown: 10,929 km/toe, MIRAI: 29,466 km/toe.

Table 3.10 Basic FCB Scenario in Japan (2040)

(a)	Diesel consumption for Transport in 2040	22.7 Mtoe	ERIA Outlook
(b)	Assumed travel distance of bus	41,000 km/Bus/Year	*1
(c)	Estimated fuel economy of diesel engine bus	4 km/Litre	*2
(d)	Number of FCBs in 2040	2,000	Figure 3.4
(e)	Replaced diesel consumption by FCB	0.02 Mtoe	(b)/(c)*(d)
(f)	Share of FCB fuel consumption	0.02%	(e)/(a)

FCB = fuel cell bus, Mtoe = million tonnes of oil equivalent.

Note: *1 Fixed route buses, calculated by the example of Yokohama City Bus (2002). FCBs are assumed to be fixed route buses.

*2 Ministry of Land, Infrastructure, Transport and Tourism

Source: Author.

Next, other countries' scenario is assumed, with Japan's scenario applied directly to OECD countries and half applied to non-OECD countries. Table 3.11 shows the FCB scenarios, which consist of the share of hydrogen in diesel consumption for transport in 2040.

Table 3.11 FCB Scenarios

Scenario	Japan and other OECD	Non-OECD
Scenario 1	0.05%	0.025%
Scenario 2	(Japan's basic scenario) 0.1%	0.05%
Scenario 3	0.2%	0.1%

Source: Author.

Due to a lack of information, FCB fuel mileage is assumed to be the same as for a conventional diesel-powered bus.

4.1.4 Assumption of Diesel Consumption for Rail Transport in 2040

Table 3.12 shows the assumed diesel consumption for rail transport in 2040, when a percentage of the diesel locomotive fleet will have been converted to FCTs. When the country data for actual rail transport diesel consumption are not available, the share is assumed to become 10% in 2040.

Table 3.12 Assumed Share of Diesel Consumption for Rail Transport in 2040

Country	2016	2040
Brunei Darussalam	-	-
Cambodia	19%	19%
Indonesia	N/A	10%
Lao PDR	N/A	10%
Malaysia	N/A	10%
Myanmar	61%	61%
Philippines	N/A	10%
Singapore	-	-
Thailand	1%	1%
Viet Nam	N/A	10%
Australia	8%	8%
China	3%	3%
India	5%	5%
Japan	1%	1%
Republic of Korea	1%	1%
New Zealand	2%	2%

Lao PDR = Lao People's Democratic Republic.
Source: 2016 data; World Energy Balances 2018 database, International Energy Agency.

For rail transport, 10% of diesel fuel consumption is assumed to be converted to hydrogen as the basic scenario. Table 3.13 shows the FCT scenarios, which consist of the share of hydrogen in diesel consumption for rail transport in 2040.

Table 3.13 FCT Scenarios

Scenario	EAS Countries
Scenario 1	5%
Scenario 2	(basic scenario) 10%
Scenario 3	20%

EAS = East Asia Summit, FCT = fuel cell train.
Source: Author.

To calculate FCT hydrogen demand, the fuel mileage difference between diesel and hydrogen locomotives should be considered. However, due to lack of necessary information, FCT fuel mileage is assumed to be same as that for conventional diesel locomotives.

4.2. Hydrogen Demand Potential for Transport Sector

4.2.1. Hydrogen Demand Potential for PFCV

Table 3.14 shows the PFCV hydrogen demand potential by country in 2040. The calculation method is described in Appendix 3.4.

Table 3.14 PFCV Hydrogen Demand Potential for 2040(in Mtoe)

Country	Scenario 1	Scenario 2	Scenario 3
Brunei Darussalam	0.0	0.0	0.0
Cambodia	0.0	0.0	0.1
Indonesia	0.3	1.4	2.7
Lao PDR	0.0	0.0	0.0
Malaysia	0.1	0.6	1.1
Myanmar	0.0	0.2	0.4
Philippines	0.0	0.1	0.2
Singapore	0.0	0.0	0.0
Thailand	0.0	0.2	0.3
Viet Nam	0.0	0.2	0.5
ASEAN	**0.5**	**2.7**	**5.4**
Australia	0.1	0.5	1.0
China	0.9	4.6	9.3
India	0.5	2.7	5.4
Japan	0.2	1.0	1.9
Republic of Korea	0.1	0.3	0.6
New Zealand	0.0	0.1	0.2
Other than ASEAN	**1.8**	**9.2**	**18.4**
Total	**2.4**	**11.9**	**23.8**

ASEAN = Association of Southeast Asian Nations, Lao PDR = Lao People’s Democratic Republic, Mtoe = million tonnes of oil equivalent, PFCV = passenger fuel cell vehicles.
Source: Author.

4.2.2. Hydrogen Demand Potential for FCB

Table 3.15 shows the FCB hydrogen demand potential by country in 2040. The calculation method is described in Appendix 3.5.

Table 3.15 FCB Hydrogen Demand Potential in 2040 (in Mtoe)

Country	Scenario 1	Scenario 2	Scenario 3
Brunei Darussalam	0.00	0.00	0.00
Cambodia	0.00	0.00	0.00
Indonesia	0.02	0.04	0.08
Lao PDR	0.00	0.00	0.00
Malaysia	0.00	0.01	0.02
Myanmar	0.00	0.00	0.00
Philippines	0.00	0.01	0.01
Singapore	0.00	0.00	0.00
Thailand	0.00	0.01	0.02
Viet Nam	0.01	0.01	0.02
ASEAN	**0.04**	**0.08**	**0.16**
Australia	0.00	0.01	0.01
China	0.05	0.09	0.18
India	0.03	0.06	0.13
Japan	0.01	0.02	0.03
Republic of Korea	0.00	0.01	0.02
New Zealand	0.00	0.00	0.00
Other than ASEAN	**0.09**	**0.18**	**0.37**
Total	**0.13**	**0.27**	**0.53**

ASEAN = Association of Southeast Asian Nations, Lao PDR = Lao People's Democratic Republic, FCB = fuel cell bus.

Source: Author.

4.2.3 Hydrogen Demand Potential for FCT

Table 3.16 shows the FCT hydrogen demand potential by country in 2040. The calculation method is described in Appendix 3.6.

Table 3.16 FCT Hydrogen Demand Potential for 2040 (in Mtoe)

Country	Scenario 1	Scenario 2	Scenario 3
Brunei Darussalam	-	-	-
Cambodia	0.02	0.04	0.08
Indonesia	0.42	0.85	1.70
Lao PDR	0.01	0.01	0.02
Malaysia	0.10	0.19	0.39
Myanmar	0.03	0.05	0.10
Philippines	0.06	0.12	0.25
Singapore	-	-	-
Thailand	0.01	0.01	0.02
Viet Nam	0.11	0.23	0.46
ASEAN	**0.75**	**1.51**	**3.02**
Australia	0.05	0.10	0.20
China	0.24	0.47	0.94
India	0.31	0.61	1.22
Japan	0.01	0.01	0.02
Republic of Korea	0.00	0.01	0.02
New Zealand	0.00	0.00	0.01
Other than ASEAN	**0.60**	**1.21**	**2.42**
Total	**1.36**	**2.72**	**5.44**

ASEAN = Association of Southeast Asian Nations, FCT = fuel cell train, Lao PDR = Lao People's Democratic Republic, Mtoe = million tonnes of oil equivalent.
Source: Author.

4.2.4 Hydrogen Demand Potential for Transport Sector (Summary)

Table 3.17 summarises the hydrogen demand potential for the transport sector by country in 2040.

Table 3.17 Summary of Transport Sector Hydrogen Demand Potential for 2040 (in Mtoe)

Country	Scenario 1				Scenario 2				Scenario 3			
	PFCV	FCB	FCT	Total	PFCV	FCB	FCT	Total	PFCV	FCB	FCT	Total
Brunei Darussalam	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Cambodia	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.0	0.1	0.1
Indonesia	0.3	0.0	0.4	0.7	1.4	0.0	0.8	2.3	2.7	0.1	1.7	4.5
Lao PDR	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Malaysia	0.1	0.0	0.1	0.2	0.6	0.0	0.2	0.8	1.1	0.0	0.4	1.5
Myanmar	0.0	0.0	0.0	0.1	0.2	0.0	0.1	0.3	0.4	0.0	0.1	0.5
Philippines	0.0	0.0	0.1	0.1	0.1	0.0	0.1	0.2	0.2	0.0	0.2	0.5
Singapore	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Thailand	0.0	0.0	0.0	0.0	0.2	0.0	0.0	0.2	0.3	0.0	0.0	0.4
Viet Nam	0.0	0.0	0.1	0.2	0.2	0.0	0.2	0.5	0.5	0.0	0.5	1.0
ASEAN	**0.5**	**0.0**	**0.8**	**1.3**	**2.7**	**0.1**	**1.5**	**4.3**	**5.4**	**0.2**	**3.0**	**8.6**
Australia	0.1	0.0	0.1	0.1	0.5	0.0	0.1	0.6	1.0	0.0	0.2	1.2
China	0.9	0.0	0.2	1.2	4.6	0.1	0.5	5.2	9.3	0.2	0.9	10.4
India	0.5	0.0	0.3	0.9	2.7	0.1	0.6	3.4	5.4	0.1	1.2	6.8
Japan	0.2	0.0	0.0	0.2	1.0	0.0	0.0	1.0	1.9	0.0	0.0	2.0
Republic of Korea	0.1	0.0	0.0	0.1	0.3	0.0	0.0	0.3	0.6	0.0	0.0	0.7
New Zealand	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.1	0.2	0.0	0.0	0.2
Other than ASEAN	**1.8**	**0.1**	**0.6**	**2.5**	**9.2**	**0.2**	**1.2**	**10.6**	**18.4**	**0.4**	**2.4**	**21.2**
Total	**2.4**	**0.1**	**1.4**	**3.9**	**11.9**	**0.3**	**2.7**	**14.9**	**23.8**	**0.5**	**5.4**	**29.8**

ASEAN = Association of Southeast Asian Nations, FCB = fuel cell bus, FCT = fuel cell train, Lao PDR = Lao People's Democratic Republic, Mtoe = million tonnes of oil equivalent, PFCV = passenger fuel cell vehicle.
Source: Author.

4.3. Summary of Hydrogen Demand Potential

4.3.1. Summary of Scenarios

Table 3.18 summarises the scenarios.

Table 3.18 Summary of Scenarios

Sector	Fuel		Scenario 1	Scenario 2	Scenario 3
Electricity generation	Coal	20% of new coal-fired electricity generation will be converted to natural gas and H_2 mixed fuel-fired generation	H_2 concentration of mixed fuel		
			H_2: 10% Nat gas: 90%	H_2: 20% Nat gas: 80%	H_2: 30% Nat gas: 70%
	Natural gas	20% of new natural gas-fired electricity generation will be converted to natural gas and H_2 mixed fuel-fired generation			
Industry	Natural gas	20% of natural gas consumption for industrial purpose will be replaced by natural gas and H_2 mixed fuel			
Transport	Gasoline	Passenger Fuel Cell Vehicle: Gasoline demand will be converted to H_2	Share of H_2/ gasoline for passenger car		
			OECD H_2: 2.0% Gasoline: 98% Non-OECD H_2: 1.0% Gasoline: 99%	OECD H_2: 10% Gasoline: 90% Non-OECD H_2: 5% Gasoline: 95%	OECD H_2: 20% Gasoline: 80% Non-OECD H_2: 10% Gasoline: 90%
	Diesel	Fuel Cell Bus: Diesel demand will be converted to H_2	Share of H_2/ diesel for bus		
			Japan H_2: 0.05% Gasoline: 99.95% Other countries H_2: 0.025% Gasoline: 99.975%	Japan H_2: 0.1% Gasoline: 99.9% Other countries H_2: 0.05% Gasoline: 99.95%	Japan H_2: 0.2% Gasoline: 99.8% Other countries H_2: 0.1% Gasoline: 99.9%
	Diesel	Fuel Cell Train: Diesel consumption for rail transport will be converted to H_2	Share of H_2/ diesel for rail transport)		
			H_2: 5% Diesel: 95%	H_2: 10% Diesel: 90%	H_2: 20% Diesel: 80%

Source: Author.

4.3.2 Summary of Hydrogen Demand Potential in ASEAN and EAS

Table 3.19 shows hydrogen demand potential by country in 2040. The potential of ASEAN is projected as 6.6 Mtoe in Scenario 1, 14.9 Mtoe in Scenario 2, and 24.4 Mtoe in Scenario 3. The potential of the EAS region is projected as 28.9 Mtoe in Scenario 1, 64.9 Mtoe in Scenario 2, and 104.7 Mtoe in Scenario 3.

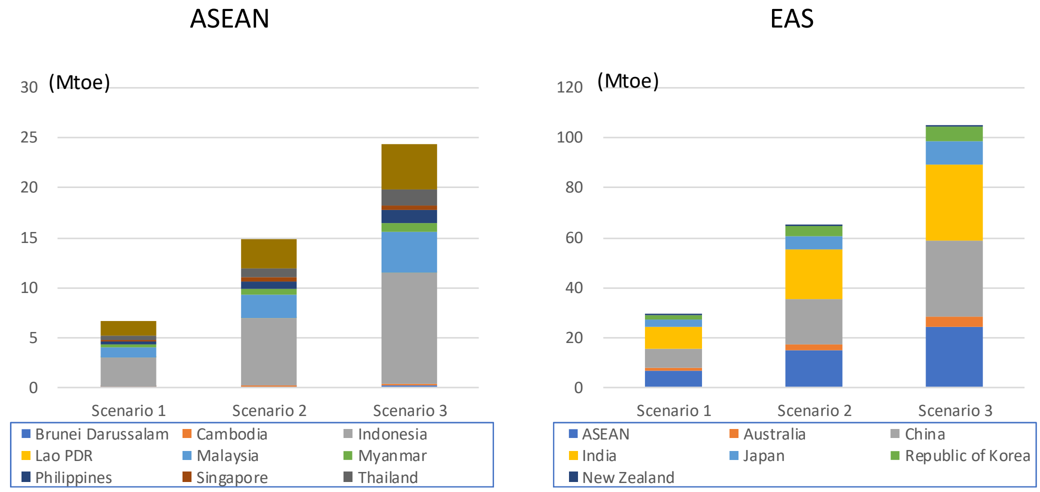
Table 3.19 Summary of Hydrogen Demand Potential in 2040 (in Mtoe)

	Scenario 1				Scenario 2				Scenario 3			
Country	Electricity	Industry	Transport	Total	Electricity	Industry	Transport	Total	Electricity	Industry	Transport	Total
Brunei Darussalam	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.1	0.1	0.0	0.0	0.1
Cambodia	0.0	0.0	0.0	0.1	0.1	0.0	0.1	0.2	0.1	0.0	0.1	0.3
Indonesia	1.9	0.3	0.7	2.9	0.0	0.0	2.3	6.6	5.8	0.8	4.5	11.1
Lao PDR	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Malaysia	0.6	0.3	0.2	1.0	1.1	0.5	0.8	2.4	1.7	0.8	1.5	4.0
Myanmar	0.1	0.0	0.1	0.2	0.2	0.1	0.3	0.5	0.3	0.1	0.5	0.9
Philippines	0.3	0.0	0.1	0.4	0.6	0.0	0.2	0.9	0.9	0.0	0.5	1.4
Singapore	0.1	0.0	0.0	0.1	0.2	0.1	0.0	0.3	0.3	0.1	0.0	0.5
Thailand	0.2	0.2	0.0	0.5	0.5	0.4	0.2	1.0	0.7	0.6	0.4	1.6
Viet Nam	1.1	0.1	0.2	1.4	2.1	0.3	0.5	2.9	3.2	0.4	1.0	4.6
ASEAN	4.4	0.9	1.3	6.6	8.7	1.8	4.3	14.9	13.1	2.8	8.6	24.4
Australia	0.7	0.2	0.1	1.0	1.4	0.3	0.6	2.3	2.1	0.5	1.2	3.8
China	4.8	1.8	1.2	7.9	9.7	3.6	5.2	18.5	14.5	5.4	10.4	30.3
India	7.4	0.7	0.9	9.0	14.8	1.3	3.4	19.5	22.3	2.0	6.8	31.0
Japan	2.0	0.3	0.2	2.5	4.0	0.6	1.0	5.6	6.0	0.9	2.0	8.9
Republic of Korea	1.5	0.2	0.1	1.8	3.1	0.4	0.3	3.9	4.6	0.7	0.7	6.0
New Zealand	0.0	0.0	0.0	0.1	0.1	0.0	0.1	0.2	0.1	0.1	0.2	0.3
Other than ASEAN	16.5	3.2	2.5	22.2	33.1	6.4	10.6	50.0	49.6	9.5	21.2	80.3
Total	20.9	4.1	3.9	28.9	41.8	8.2	14.9	64.9	62.7	12.3	29.8	104.7

ASEAN = Association of Southeast Asian Nations, Lao PDR = Lao People's Democratic Republic, Mtoe = million tonnes of oil equivalent.
Source: Author.

Figure 3.5 shows the hydrogen demand potential by country in 2040. Indonesia has the largest hydrogen demand potential amongst ASEAN member countries, followed by Malaysia and Viet Nam. China has the largest hydrogen demand potential in the EAS region, followed by India and ASEAN total.

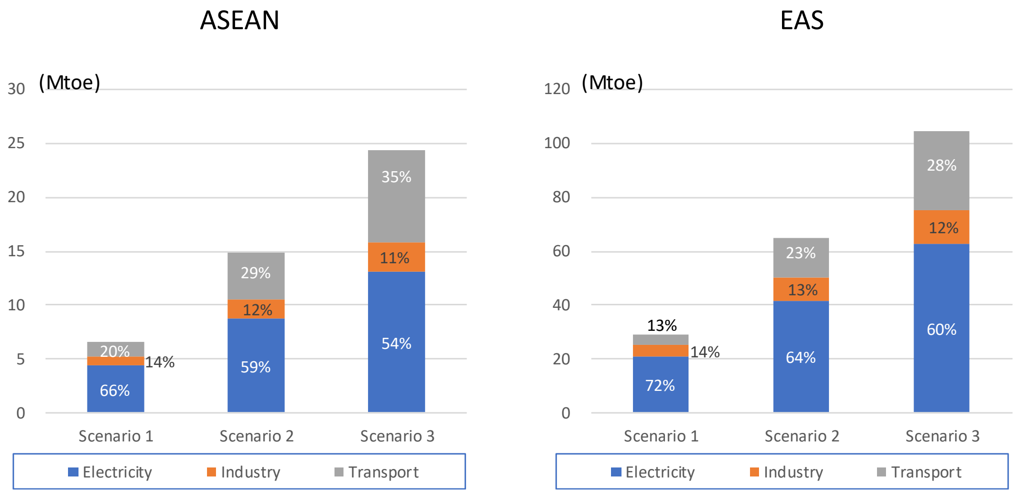
Figure 3.5 Hydrogen Demand Potential by Country



ASEAN = Association of Southeast Asian Nations, EAS = East Asia Summit, Lao PDR = Lao People's Democratic Republic, Mtoe = million tonnes of oil equivalent.
Source: Author.

Figure 3.6 shows the hydrogen demand potential by sector in 2040. Electricity generation has the largest hydrogen demand potential in all scenarios in both ASEAN and the EAS region. Country analysis is shown in Appendix 3.7.

Figure 3.6 Hydrogen Demand Potential by Sector



ASEAN = Association of Southeast Asian Nations, EAS = East Asia Summit, Mtoe = million tonnes of oil equivalent.
Source: Author.

5.Competitive Hydrogen Prices from a Demand-Side Point of View

In this section, the price competitiveness of hydrogen compared with conventional fuel is calculated by sector. Two cases of prices, without CO_2 premium and with CO_2 premium, are estimated. Because the comparison is made only for hydrogen's potential as a fuel, it does not calculate end-use cost difference, e.g. capital expenditure to build a plant and its operating cost.

Electricity generation sector: Compare with import prices of fossil fuel

Industry sector: Compare with current natural gas retail price for Industry in Japan

Transport sector: Compare with current gasoline retail price in Indonesia and Japan

5.1. Basic Assumption and Conversion Factor for Calculation

Table 3.20 shows the assumption of prices.

Table 3.20 Assumption of Prices

Sector	Fuel	Price	Source
Electricity generation	Imported Coal	\$10.0/ MMbtu (\$397/ toe)	New Policy Scenario, WEO 2018, IEA Average of Japan and Coastal China
	Imported Natural gas	\$92/ tonne (\$150/ toe)	New Policy Scenario, WEO 2018, IEA Average of China and Japan
Industry	Natural gas for Industry	\$547.4/ toe	Energy Prices and Taxes Q3 2018, IEA 2017. Japan
Transport	Retail price of Gasoline (Indonesia)	\$84.39/ BOE (\$0.531/ L)	Handbook of Energy & Economic Statistics of Indonesia 2017
	Retail price of Gasoline (Japan)	\$1.19/ L (tax incl.) \$0.597/ L (tax excl.)	2017 Japan. Energy Prices and Taxes Q32018, IEA The share of tax: 49.8%
All sectors	CO_2	\$41/ tonne	2040 (2017 price), New Policy Scenario, WEO 2018, IEA Average of China, European Union and Republic of Korea

BOE = barrel oil equivalent, IEA = International Energy Agency, MMbtu = millions of BTUs, toe = tonnes of oil equivalent, WEO = World Energy Outlook.
Source: Author.

Table 3.21 shows other assumptions and conversion factors.

Table 3.21 Other Assumptions and Conversion Factors

Carbon content	Coal: 25.8 kg-C/GJ (=3.961 tonne-CO_2/toe-input) Natural gas: 15.3 kg-C/GJ (=2.349 tonne-CO_2/toe-input) Gasoline: 18.9 kg-C/GJ (=2.902 tonne-CO_2/toe) (=2.269 tonne-CO_2/KL)	Source: CO_2 Emissions from Fuel Combustion 2018, IEA
NCV	Other Bituminous Coal (Australian export coal) 0.6138 toe/tonne	Source: World Energy Balances 2018 database, IEA
H_2 specification	Gas density: 0.0835 kg/m^3 NCV: 10,780 kJ/m^3 = 2,575 kcal/m^3 = 30,834 kcal/kg = 3,884 m^3/toe	Source: Iwatani Corporation
Thermal efficiency (Electricity generation)	Coal: 55% Natural gas: 63% H_2: 63%	Source: High Efficiency of Thermal Power, November 2017, ANRE, METI
Conversion factor	1GJ = 0.02388 toe 1cal = 4.187 J 1Gcal = 0.1 toe 1MWh = 0.086 toe 1MMbtu = 0.0252 toe	-

ANRE = Agency for Natural Resources and Energy, IEA = International Energy Association, METI = Ministry of Economy, Trade, and Industry, Japan, NCV = net calorific value, toe = tonnes of oil equivalent.
Source: Author.

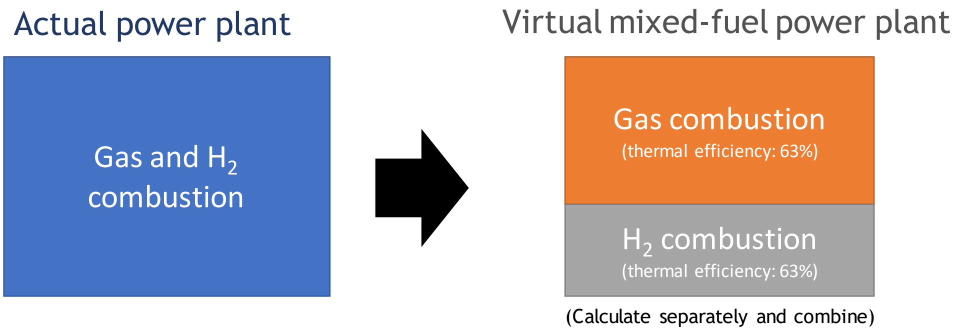
5.2. Estimated Competitive Hydrogen Prices for Electricity Generation

In this study, estimated hydrogen prices for electricity generation are defined as follows:

Coal (or natural gas) consumption * unit price = Hydrogen consumption * competitive price

To calculate competitive hydrogen prices with or without CO_2 premium, natural gas and hydrogen are separately calculated in a virtual mixed fuel, as shown in Figure 3.7.

Figure 3.7 Virtual Mixed-Fuel Power Plant



Source: Author.

Table 3.22 shows the competitive price of hydrogen for electricity generation.

Table 3.22 Estimated Competitive Price of Hydrogen for Electricity Generation (in US dollars)

Without CO_2 Premium		With CO_2 Premium	
vs. Coal	vs. Natural gas	vs. Coal	vs. Natural gas
($/toe)	($/toe)	($/toe)	($/toe)
172*1	397	274	458
($/m^3)	($/m^3)	($/m^3)	($/m^3)
0.044	0.102	0.071	0.118

toe = tonnes of oil equivalent.
Note: *1: Due to difference of thermal efficiency, coal requires more energy to generate the same amount of electricity as compared to natural gas.
Source: Author.

5.3 Estimated Competitive Hydrogen Prices for Industry

Table 3.23 shows the estimated competitive hydrogen prices for industry.

Table 3.23 Estimated Competitive Price of Hydrogen for Industry(in US dollars)

Without CO_2 Premium vs. Natural gas	With CO_2 Premium vs. Natural gas
($/toe) 547.4	($/toe) 643.7
($/m^3) 0.141	($/m^3) 0.166

toe = tonnes of oil equivalent.
Source: Author.

5.4. Estimated Competitive Hydrogen Prices for Transport

In this section, the competitive hydrogen price for PFCVs is compared with the gasoline price for an internal combustion engine car. The TOYOTA MIRAI is selected as a PFCV and the TOYOTA CROWN is selected as the internal combustion engine vehicle because dimensions are similar.

Table 3.24 shows the comparison between TOYOTA CROWN and TOYOTA MIRAI.

Table 3.24 Comparison between TOYOTA CROWN and TOYOTA MIRAI

	CROWN	MIRAI
Appearance		
Dimensions (cm) Length	4,910	4,890
Width	1,800	1,815
Height	1,455	1,535
Weight (kg)	1,590–1,650	1,850
Displacement	2,000 cc	
Fuel mileage (JC08 mode)	12.8 km/litre *1	7.59 km/ m^3 *2
Fuel consumption per 100 km	7.81 litre	13.18 m^3

Note: *1 Source: TOYOTA MOTOR CORPORATION
*2 MIRAI's fuel tank capacity: 122.4 L, pressure: 70 Mpa => 85.68 m^3-H_2/full load
MIRAI can run 650 km/ full load of H_2.

Table 3.25 shows the expense of driving the TOYOTA CROWN 100 km, assuming gasoline consumption of 7.81 litre in JC08 mode, with gasoline prices in Japan and Indonesia being $0.597/litre and $0.531/litre, respectively.

Table 3.25 Expense of 100 km Driving of TOYOTA CROWN (In US dollars)

	Japan	Indonesia
Expense	$4.67	$4.15

Source: Author.

TOYOTA MIRAI consumes 13.18m^3 of hydrogen for 100 km driving. Table 3.26 shows the competitive price of hydrogen for PFCVs in Japan and Indonesia against the expense of 100 km driving of TOYOTA CROWN.

Table 3.26 Estimated Competitive Price of Hydrogen for PFCVs (In US dollars)

	Japan	Indonesia
Without CO_2 Premium	$0.354/ m^3 ($1,375/ toe)	$0.315/m^3 ($1,222/ toe)
With CO_2 Premium	$0.417/ m^3 ($1,621/ toe)	$0.378/m^3 ($1,467/ toe)

toe = tonnes of oil equivalent.
Source: Author.

5.5. Estimated Competitive Hydrogen Prices (Summary)

Table 3.27 shows the summary of estimated competitive price of hydrogen. Hydrogen costs should be reduced to enable market penetration.

Table 3.27 Estimated Competitive Hydrogen Prices(In US dollars)

Sector	Fuel	Without CO_2 premium ($/toe)	Without CO_2 premium ($/m^3)	With CO_2 premium ($/toe)	With CO_2 premium ($/m^3)
Electricity	Coal	172	0.044	274	0.071
	Natural gas	397	0.102	458	0.118
Industry	Natural gas	547	0.141	644	0.166
Transport	Gasoline				
	Japan	1,375	0.354	1,589	0.409
	Indonesia	1,222	0.315	1,436	0.370

toe = tonnes of oil equivalent.
Note: Capital expenditure and operating expenditure (except fuel) of end-use item differences between conventional energy and hydrogen are not considered.
Source: Author.

In this study, import price and CO_2 price draw on 2040 projections in the WEO 2018 New Policy Scenario. WEO 2018 offered the Sustainable Development Scenario in addition to the New Policy Scenario, which assumes stronger climate actions and a higher CO_2 cost of $133/tonne that could increase price competitiveness of clean hydrogen. Tables 3.28 and 3.29 summarise the estimated competitive hydrogen prices, drawing on the Sustainable Development Scenario as an alternative case.

Because of a resulting increased CO_2 cost environment, stronger climate policies can support expanded use of clean hydrogen.

Table 3.28 Estimated Competitive Hydrogen Prices (Sustainable Development Scenario)
(In US dollars)

Sector	Fuel	Without CO_2 premium ($/toe)	Without CO_2 premium ($/m^3)	With CO_2 premium ($/toe)	With CO_2 premium ($/m^3)
Electricity	Coal	140	0.036	472	0.121
	Natural gas	345	0.089	542	0.140
Industry	Natural gas	547	0.141	860	0.221
Transport	Gasoline				
	Japan	1,375	0.354	2,070	0.533
	Indonesia	1,222	0.315	1,917	0.493

toe = tonnes of oil equivalent.
Note: Capital expenditure and operating expenditure (except fuel) of end-use item differences between conventional energy and hydrogen are not considered.
Source: Author.

Table 3.29 Assumptions (Sustainable Development Scenario) (In US dollars)

Sector	Fuel	Price
Import price	Coal	$75/tonne ($150/toe)
	Natural gas	$8.70/MMbtu ($397/toe)
CO_2 price	CO_2	$133/tonne-$CO_2$
For Industry	Natural gas	$547.40/toe
Transport	Gasoline	Japan: $0.597/litre Indonesia: $0.531/litre

Thermal efficiency	
Coal	55%
Natural gas	63%
H_2	63%

toe = tonnes of oil equivalent.
Note: Letters in red = Sustainable Development Scenario.
Source: Author.

6. Estimated Reduction of Fossil Fuel Consumption and CO_2 Emissions

This section analyses how introducing hydrogen into the energy mix reduces fossil fuel consumption and, hence, CO_2 emissions. The calculation method and sectoral analysis are presented in Appendices 3.8 to 3.13.

6.1. Estimated Reduction of Fossil Fuel Consumption

Table 3.30 shows the projected energy replaced by hydrogen in 2040. Natural gas demand will increase in many countries because 20% of coal consumption will be replaced by natural gas and hydrogen mixed fuel in electricity generation.

Table 3.30 Replaced Energy by Hydrogen in 2040

Country	Scenario 1				Scenario 2				Scenario 3			
	Coal (Mln tonnes)	Nat gas (Bcm)	Gasoline (000 tonnes)	Diesel (000 tonnes)	Coal (Mln tonnes)	Nat gas (Bcm)	Gasoline (000 tonnes)	Diesel (000 tonnes)	Coal (Mln tonnes)	Nat gas (Bcm)	Gasoline (000 tonnes)	Diesel (000 tonnes)
Brunei Darussalam	-0.1	0.1	-6	-0	-0.1	0.1	-30	-0	-0.1	0.0	-59	-0
Cambodia	-0.3	0.3	-13	-20	-0.3	0.2	-66	-41	-0.3	0.2	-132	-82
Indonesia	-15.4	13.4	-691	-437	-15.4	11.6	-3,455	-875	-15.4	9.8	-6,909	-1,750
Lao PDR			-2	-6			-12	-13			-24	-26
Malaysia	-2.3	1.5	-281	-100	-2.3	1.0	-1,403	-200	-2.3	0.5	-2,806	-399
Myanmar	-0.7	0.6	-107	-25	-0.7	0.5	-536	-50	-0.7	0.4	-1,072	-100
Philippines	-1.9	1.6	-59	-64	-1.9	1.4	-295	-128	-1.9	1.2	-590	-257
Singapore	-0.0	-0.1	-8	-0	-0.0	-0.2	-42	-1	-0.0	-0.2	-84	-1
Thailand	-1.1	0.7	-84	-11	-1.1	0.4	-418	-21	-1.1	0.1	-837	-42
Viet Nam	-9.1	8.0	-123	-118	-9.1	7.0	-615	-235	-9.1	5.9	-1,230	-470
ASEAN	-31.0	26.1	-1,374	-782	-31.0	22.0	-6,871	-1,564	-31.0	17.9	-13,743	-3,128
Australia	-4.0	3.1	-245	-52	-4.0	2.5	-1,225	-105	-4.0	2.0	-2,450	-209
China	-21.9	15.3	-2,349	-276	-21.9	11.2	-11,745	-553	-21.9	7.1	-23,490	-1,106
India	-71.7	64.6	-1,369	-332	-71.7	56.6	-6,844	-664	-71.7	48.6	-13,689	-1,327
Japan	-9.5	7.2	-489	-13	-9.5	6.0	-2,443	-26	-9.5	4.7	-4,885	-51
Republic of Korea	-8.6	7.0	-163	-9	-8.6	5.9	-814	-17	-8.6	4.8	-1,629	-34
New Zealand	0.0	-0.1	-42	-3	0.0	-0.1	-210	-5	0.0	-0.1	-419	-10
Other than ASEAN	-115.6	97.3	-4,656	-684	-115.6	82.2	-23,281	-1,369	-115.6	67.0	-46,562	-2,737
Total	-146.6	123.4	-6,031	-1,466	-146.6	104.2	-30,153	-2,933	-146.6	84.9	-60,305	-5,866

ASEAN = Association of Southeast Asian Nations, Lao PDR = Lao People's Democratic Republic.
Source: Author.

6.2. Estimated CO_2 Emission Reduction

Table 3.31 shows the total CO_2 emissions from fuel combustion by scenario in ASEAN and the EAS region. CO_2 emissions can be reduced by up to 2.7% depending on the scenario, compared to the ERIA benchmark outlook.

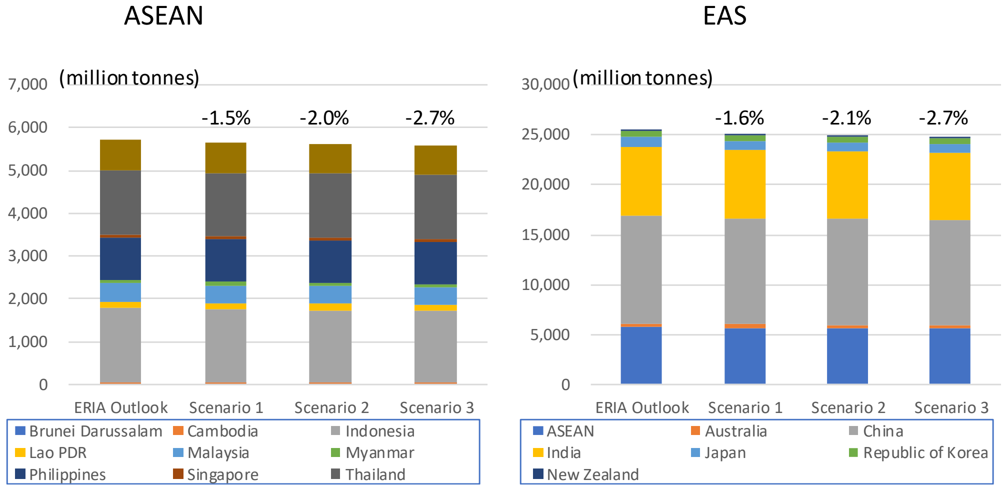
Table 3.31 Total CO_2 Emissions from Fuel Combustion in 2040

	Total CO_2 emissions (million tonnes)				CO_2 emission reduction		
	ERIA Outlook	Scenario 1	Scenario 2	Scenario 3	Scenario 1	Scenario 2	Scenario 3
Brunei Darussalam	16.0	15.6	15.5	15.3	-2.0%	-3.1%	-4.2%
Cambodia	27.9	27.0	26.6	26.2	-3.1%	-4.4%	-6.0%
Indonesia	1,745.9	1,704.3	1,689.2	1,670.6	-2.4%	-3.2%	-4.3%
Lao PDR	150.1	150.1	150.0	150.0	0.0%	-0.1%	-0.1%
Malaysia	426.3	418.3	412.6	405.7	-1.9%	-3.2%	-4.8%
Myanmar	85.7	83.4	81.7	79.6	-2.7%	-4.7%	-7.1%
Philippines	996.0	990.8	989.2	987.1	-0.5%	-0.7%	-0.9%
Singapore	62.9	62.5	62.1	61.6	-0.6%	-1.3%	-2.1%
Thailand	1,503.8	1,500.2	1,498.1	1,495.8	-0.2%	-0.4%	-0.5%
Viet Nam	715.8	692.8	688.1	682.7	-3.2%	-3.9%	-4.6%
ASEAN	**5,730.4**	**5,645.1**	**5,613.2**	**5,574.6**	**-1.5%**	**-2.0%**	**-2.7%**
Australia	367.8	356.3	351.1	344.9	-3.1%	-4.5%	-6.2%
China	10,746.7	10,676.3	10,630.8	10,577.1	-0.7%	-1.1%	-1.6%
India	6,943.3	6,766.2	6,729.2	6,687.0	-2.6%	-3.1%	-3.7%
Japan	965.6	938.5	927.0	914.0	-2.8%	-4.0%	-5.3%
Rep. of Korea	670.2	647.1	640.9	634.2	-3.4%	-4.4%	-5.4%
New Zealand	29.1	28.8	28.2	27.4	-0.9%	-3.1%	-5.8%
Other than ASEAN	**19,722.6**	**19,413.3**	**19,307.2**	**19,184.6**	**-1.6%**	**-2.1%**	**-2.7%**
Total	**25,452.9**	**25,058.3**	**24,920.4**	**24,759.2**	**-1.6%**	**-2.1%**	**-2.7%**

ASEAN = Association of Southeast Asian Nations, ERIA = Economic Research Institute of ASEAN and East Asia, Lao PDR = Lao People's Democratic Republic.
Source: Author.

Figure 3.8 shows the total CO_2 emissions from fuel combustion by country. Indonesia has the largest CO_2 emissions reduction potential in ASEAN member countries, while India has the largest CO_2 emissions reduction potential despite being the second-largest emitter in the EAS region. Country-wise analysis is described in Appendix 3.14.

Figure 3.8 Total CO_2 Emissions from Fuel Combustion by Country



ASEAN = Association of Southeast Asian Nations, EAS = East Asia Summit, Lao PDR = Lao People's Democratic Republic.

Source: Author.

Table 3.32 shows the economic impact of CO_2 emissions reduction by country. The economic impact is calculated by multiplying CO_2 emissions reduction amount by the CO_2 price. Other elements are not considered. The price of CO_2 in 2040 is assumed to be \$41/tonne-CO_2.

In ASEAN, the economic impact of CO_2 emissions reduction is \$3.5 billion in Scenario 1, \$4.8 billion in Scenario 2, and \$6.4 billion in Scenario 3. In the EAS region, the economic impact of CO_2 emissions reduction reaches \$16.2 billion in Scenario 1, \$21.8 billion in Scenario 2, and \$28.4 billion in Scenario 3.

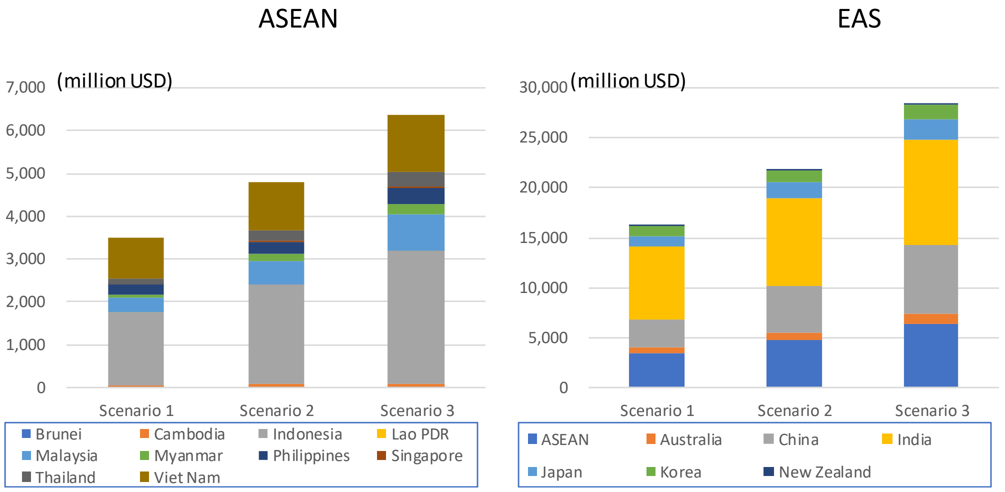
Table 3.32 Economic Impact of CO_2 Emissions Reduction(in million US$)

Country	Scenario 1	Scenario 2	Scenario 3
Brunei Darussalam	13	20	27
Cambodia	36	50	68
Indonesia	1,705	2,324	3,086
Lao PDR	1	3	6
Malaysia	329	563	845
Myanmar	94	164	250
Philippines	212	280	363
Singapore	16	34	53
Thailand	147	231	326
Viet Nam	943	1,136	1,359
ASEAN	**3,497**	**4,803**	**6,385**
Australia	469	684	938
China	2,884	4,751	6,951
India	7,260	8,776	10,508
Japan	1,111	1,581	2,115
Republic of Korea	947	1,200	1,475
New Zealand	11	37	69
Other than ASEAN	**12,682**	**17,030**	**22,056**
Total	**16,179**	**21,833**	**28,442**

ASEAN = Association of Southeast Asian Nations, Lao PDR = Lao People's Democratic Republic.
Source: Author.

Figure 3.9 shows the economic impact of CO_2 emissions reduction by country. Country-wise analysis is described in Appendix 3.15.

Figure 3.9 Economic Impact of CO_2 Emissions Reduction (ASEAN and EAS)



ASEAN = Association of Southeast Asian Nations, EAS = East Asia Summit, Lao PDR = Lao People's Democratic Republic.

Source: Author.

Appendix 3.1:Useful Information to Estimate Hydrogen Demand Potential

Appendix 3.1.1. Recent technology development for hydrogen utilisation

Table A3.1.1 shows the progress of the main hydrogen utilisation technologies. While electricity generation, which is expected to have substantial hydrogen demand, is still in the demonstration stage, 100% hydrogen-fuelled industrial boilers are already commercialised; however, they are small scale and assumed to operate on industrial by-product hydrogen. It should be noted that Alstom has begun to operate fuel cell trains (FCTs) commercially in Germany.

Table A3.1.1 Recent Hydrogen Utilisation Technology Development

Purpose	Scale	Fuel	H_2 concentration	Company	Announced	NOx level	Status (Target)
Gas turbine	1,600 ℃ 700 MW class	H_2 Natural gas	30%	MHPS	19 Jan 2018	Low	Demonstration Success
Gas turbine	2 MW	NH_3 Natural gas	20%	IHI	18 April 2018	Low	Demonstration Success
Boiler (Power)	Input 10 MW	NH_3 Coal	20%	IHI	28 March 2018	Low	Demonstration Success
Gas engine	0.6 MW	H_2 Natural gas	20%	JST, SIP, AIST, Three Universities	18 May 2018	Low	Demonstration Success
Boiler (Industry)	Small	H_2 (industrial by-product)	100%	Miura, Takasago	23 Jan 2017 -	NA	Already Commercialised
Boiler (Once-Through boiler)	small?	H_2 (industrial by-product)	100%	Kawasaki Thermal engineering	14 May 2018	Low	2019 Commercialisation
FCT		H_2	100%	Alstom	11 July 2018		September 2018 Alstom has started commercial operation of FCTs in Germany

Note: AIST = National Institute of Advanced Industrial Science and Technology, FCT = fuel cell train, JST= Japan Science & Technology Agency, MHPS = Mitsubishi Hitachi Power Systems, SIP = Cross-Ministerial Strategic Innovation Promotion Program, Three Universities = Okayama, Tokyo City, Waseda.

Source: Press Releases.

Appendix 3.1.2 Example for hydrogen demand timeframe

In this section, the timeframe of hydrogen demand, as described in the documents of the Basic

Hydrogen Strategy from Japan's Ministry of Energy, Trade, and Industry (METI), the Australian Renewable Energy Agency, and the International Energy Agency (IEA), is analysed.

Appendix 3.1.2.1 Basic Hydrogen Strategy, Japan

Figure A3.1.1 shows the hydrogen demand timeframe and the scale of hydrogen demand as described in the Basic Hydrogen Strategy (Japan).

Figure A3.1.1 Basic Hydrogen Strategy, Japan

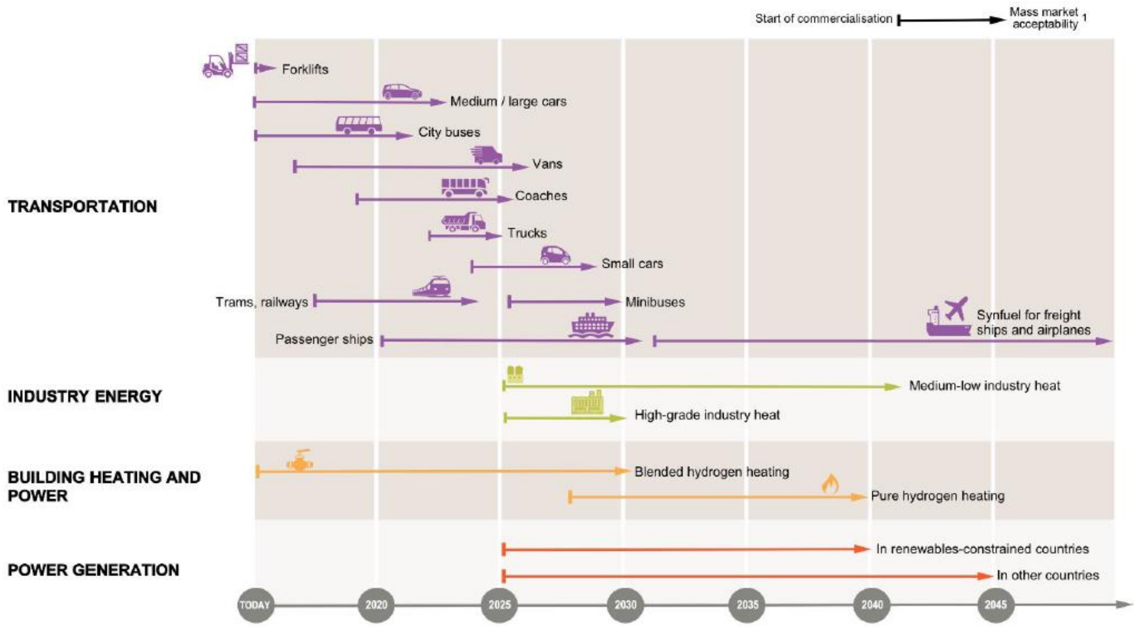
	Present	2030	Future
Electricity Generation	R&D stage	Hydrogen Procurement 300,000 tonnes/y (Equiv. 1 GW)	Hydrogen Procurement 5-10 million tonnes/y (Equiv. 15-30 GW)
Transport (Number of Vehicles)			
FCV	25,000	800,000	Replacing Conventional Gasoline Mobility Introducing Large FCVs Development and Commercialisation of FC Trucks Promote FC small ships
FC Buses	2	1,200	
Forklifts	40	10,000	
Ene-Farm [FC system for Residential] (Number of Unit)	230,000	5,300,000	Replacing Traditional Residential Energy Systems

FC = fuel cell, FCV = fuel cell vehicle.
Source: Basic Hydrogen Strategy (METI, December 2017).

Appendix 3.1.2.2 ARENA, Australia

Figure A3.1.2 shows the hydrogen demand timeframe developed by the Australian Renewable Energy Agency (ARENA), which is optimistic, as Australia has an export target.

Figure A3.1.2 Hydrogen Demand Timeframe by ARENA



ARENA = Australian Renewable Energy Agency.
Source: *Opportunities For Australia From Hydrogen Exports*, August 2018.

Appendix 3.1.2.3 Energy Technology Perspective 2017, IEA

The IEA report on energy technologies outlines how these and other trends as well as technological advances will play out in the next four decades to reshape the global energy sector. Table A3.1.2 describes the Hydrogen Demand in Energy Technology Perspective 2017, IEA.

Table A3.1.2 Hydrogen Demand in Energy Technology Perspective 2017

Sector	Hydrogen Demand
Electricity generation	Hydrogen is not mentioned in ETP 2017.
Industry	In the context of boiler fuel, hydrogen is not mentioned in ETP 2017.
Buildings	Hydrogen is not mentioned in ETP 2017. H12 Hydrogen energy deployment demonstration in Leeds (UK) is introduced. ✓ Hydrogen production with CCS ✓ Cost and complexity to conversion of gas equipment ✓ Depends on UK Government's decision to support CCS
Transport	Hydrogen contributes only a small fraction of the energy demand in the central projections developed in ETP 2017. [Share of FCVs in 2040] ➢ LDV: 1.2% at B2DS, almost zero at RTS ➢ Two- and three-wheelers: zero ➢ Bus and rail: It seems to be almost the same as LDV. ➢ Trucks: It seems to be zero in all scenarios. ➢ Aviation: The potential for aviation to move away from fossil fuels is limited. ➢ International shipping: Hydrogen is considered as additional possibilities to decarbonise international shipping beyond the 2DS and B2DS results.

CCS = carbon capture and storage, ETP = Energy Technology Perspective, FCV = fuel cell vehicle, LDV = light duty vehicles.

Note: RTS: Reference Technology Scenario (= WEO New Policy Scenario);
2DS: 2 °C Scenario (= WEO 450 Scenario);
B2DS: Beyond 2 °C Scenario (CO_2 price: $540/tonne-$CO_2$ in 2060).

Source: Energy Technology Perspective 2017, IEA.

Appendix 3.1.2.4 WEO, IEA

World Energy Outlook 2017 (WEO 2017) IEA describes hydrogen demand from blending with natural gas as follows:

> *[W]ith only minor modifications, the transmission network could cope with up to around 10% hydrogen blended into the natural gas stream.* (Altfeld and Pinchbeck, 2013)
>
> *Many existing natural gas turbines, for example, could only handle around 1% hydrogen injection for performance and safety reasons (although they may be capable of tolerating 5-15% injection with some modifications).*
>
> *Hydrogen injection could displace around 100 bcm of natural gas consumption across the global energy system in 2040.*

World Energy Outlook 2018 (WEO 2018), IEA, latest edition, describes hydrogen demand as follows:

> *To help decarbonise the buildings and industry sectors, hydrogen could be injected into existing gas networks (current regulatory blending limits are relatively low, but up to 20% of hydrogen could be injected into natural gas networks).*

Appendix 3.2 Calculation of Hydrogen Demand Potential for Electricity Generation

Table A3.2.1 Electricity Generation (ERIA Outlook) and Replaced Electricity Generation by Hydrogen

Country	Electricity generation (ERIA Outlook)						20% of new generation			20% of new generation		
	Coal			Natural gas			Coal	Natural gas	Total	Coal	Natural gas	Total
	2015 (TWh)	2040 (TWh)	New (TWh)	2015 (TWh)	2040 (TWh)	New (TWh)	(TWh)	(TWh)	(TWh)	(Mtoe)	(Mtoe)	(Mtoe)
Brunei Darussalam	0.0	3.6	3.6	3.7	14.1	10.3	0.7	2.1	2.8	0.1	0.2	0.2
Cambodia	2.1	13.0	10.9	0.0	7.0	7.0	2.2	1.4	3.6	0.2	0.1	0.3
Indonesia	130.5	681.3	550.8	58.9	220.0	161.1	110.2	32.2	142.4	9.5	2.8	12.2
Lao PDR	2.3	45.2	42.9							0.0	0.0	
Malaysia	63.5	145.8	82.4	70.0	191.4	121.4	16.5	24.3	40.8	1.4	2.1	3.5
Myanmar	0.0	26.6	26.6	6.5	13.7	7.2	5.3	1.4	6.8	0.5	0.1	0.6
Philippines	36.7	105.0	68.3	18.9	55.8	36.9	13.7	7.4	21.0	1.2	0.6	1.8
Singapore	0.6	1.1	0.5	47.9	85.6	37.7	0.1	7.5	7.6	0.0	0.6	0.7
Thailand	32.9	71.8	38.9	117.0	161.0	44.0	7.8	8.8	16.6	0.7	0.8	1.4
Viet Nam	51.0	376.4	325.4	44.9	109.6	64.6	65.1	12.9	78.0	5.6	1.1	6.7
ASEAN	**319.6**	**1,469.9**	**1,150.3**	**367.8**	**858.1**	**490.3**	**221.5**	**98.1**	**319.5**	**19.0**	**8.4**	**27.5**
Australia	158.6	141.4	141.4	52.5	118.6	118.6	28.3	23.7	52.0	2.4	2.0	4.5
China	4,109.0	4,889.0	780.0	145.3	1,139.3	994.0	156.0	198.8	354.8	13.4	17.1	30.5
India	1,041.5	3,598.9	2,557.4	68.1	230.2	162.1	511.5	32.4	543.9	44.0	2.8	46.8
Japan	343.2	337.4	337.4	409.8	390.4	390.4	67.5	78.1	145.6	5.8	6.7	12.5
Republic of Korea	236.6	308.6	308.6	122.9	255.6	255.6	61.7	51.1	112.8	5.3	4.4	9.7
New Zealand	1.9	0.0	0.0	6.9	10.4	10.4	0.0	2.1	2.1	0.0	0.2	0.2
Other than ASEAN	**5,150.5**	**9,275.4**	**4,124.9**	**213.4**	**2,144.5**	**1,931.1**	**825.0**	**386.2**	**1,211.2**	**70.9**	**33.2**	**104.2**
Total	**5,470.1**	**10,745.3**	**5,275.2**	**581.3**	**3,002.6**	**2,421.4**	**1,046.5**	**484.3**	**1,530.7**	**90.0**	**41.6**	**131.6**

ASEAN = Association of Southeast Asian Nations, ERIA = Economic Research Institute for ASEAN and East Asia, Lao PDR = Lao People's Democratic Republic, Mtoe = million tonnes of oil equivalent.

Note: OECD Countries; 2040 generation is regarded as new generation.

Source: Author.

Table A3.2.2 Required Energy Input in Replaced Electricity Generation by Hydrogen and Natural Gas Mixed Fuel

	Coal						Natural gas					
	Scenario 1 (9:1)		Scenario 2 (8:2)		Scenario 3 (7:3)		Scenario 1 (9:1)		Scenario 2 (8:2)		Scenario 3 (7:3)	
	Gas (Mtoe)	H_2 (Mtoe)	Gas (Mtoe)	H_2 (Mtoe)	Gas (Mtoe)	H_2 (Mtoe)	Gas (Mtoe)	H_2 (Mtoe)	Gas (Mtoe)	H_2 (Mtoe)	Gas (Mtoe)	H_2 (Mtoe)
Brunei Darussalam	0.1	0.0	0.1	0.0	0.1	0.0	0.3	0.0	0.2	0.1	0.2	0.1
Cambodia	0.3	0.0	0.2	0.1	0.2	0.1	0.2	0.0	0.2	0.0	0.1	0.1
Indonesia	13.5	1.5	12.0	3.0	10.5	4.5	4.0	0.4	3.5	0.9	3.1	1.3
Lao PDR	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Malaysia	2.0	0.2	1.8	0.4	1.6	0.7	3.0	0.3	2.7	0.7	2.3	1.0
Myanmar	0.7	0.1	0.6	0.1	0.5	0.2	0.2	0.0	0.2	0.0	0.1	0.1
Philippines	1.7	0.2	1.5	0.4	1.3	0.6	0.9	0.1	0.8	0.2	0.7	0.3
Singapore	0.0	0.0	0.0	0.0	0.0	0.0	0.9	0.1	0.8	0.2	0.7	0.3
Thailand	1.0	0.1	0.8	0.2	0.7	0.3	1.1	0.1	1.0	0.2	0.8	0.4
Viet Nam	8.0	0.9	7.1	1.8	6.2	2.7	1.6	0.2	1.4	0.4	1.2	0.5
ASEAN	**27.2**	**3.0**	**24.2**	**6.0**	**21.2**	**9.1**	**12.0**	**1.3**	**10.7**	**2.7**	**9.4**	**4.0**
Australia	3.5	0.4	3.1	0.8	2.7	1.2	2.9	0.3	2.6	0.6	2.3	1.0
China	19.2	2.1	17.0	4.3	14.9	6.4	24.4	2.7	21.7	5.4	19.0	8.1
India	62.8	7.0	55.9	14.0	48.9	20.9	4.0	0.4	3.5	0.9	3.1	1.3
Japan	8.3	0.9	7.4	1.8	6.4	2.8	9.6	1.1	8.5	2.1	7.5	3.2
Republic of Korea	7.6	0.8	6.7	1.7	5.9	2.5	6.3	0.7	5.6	1.4	4.9	2.1
New Zealand	0.0	0.0	0.0	0.0	0.0	0.0	0.3	0.0	0.2	0.1	0.2	0.1
Other than ASEAN	**101.4**	**11.3**	**90.1**	**22.5**	**78.8**	**33.8**	**47.4**	**5.3**	**42.2**	**10.5**	**36.9**	**15.8**
Total	**128.6**	**14.3**	**114.3**	**28.6**	**100.0**	**42.9**	**59.5**	**6.6**	**52.9**	**13.2**	**46.3**	**19.8**

ASEAN = Association of Southeast Asian Nations, Lao PDR = Lao People's Democratic Republic, Mtoe = million tonnes of oil equivalent.
Note: Thermal efficiency – Coal=55%, Natural gas=63%, Hydrogen=63%;
Hydrogen concentration (Natural gas: Hydrogen): Scenario 1=9:1, Scenario 2=8:2, Scenario 3=7:3.
Source: Author.

Table A3.2.3 Input Energy Balance of Hydrogen, Coal, and Natural Gas (1)

	Coal-fired								
	H_2 demand			New Natural gas demand			Replaced Coal		
	S-1 (Mtoe)	S-2 (Mtoe)	S-3 (Mtoe)	S-1 (Mtoe)	S-2 (Mtoe)	S-3 (Mtoe)	S-1 (Mtoe)	S-2 (Mtoe)	S-3 (Mtoe)
Brunei Darussalam	0.0	0.0	0.0	0.1	0.1	0.1	-0.1	-0.1	-0.1
Cambodia	0.0	0.1	0.1	0.3	0.2	0.2	-0.2	-0.2	-0.2
Indonesia	1.5	3.0	4.5	13.5	12.0	10.5	-9.5	-9.5	-9.5
Lao PDR									
Malaysia	0.2	0.4	0.7	2.0	1.8	1.6	-1.4	-1.4	-1.4
Myanmar	0.1	0.1	0.2	0.7	0.6	0.5	-0.5	-0.5	-0.5
Philippines	0.2	0.4	0.6	1.7	1.5	1.3	-1.2	-1.2	-1.2
Singapore	0.0	0.0	0.0	0.0	0.0	0.0	-0.0	-0.0	-0.0
Thailand	0.1	0.2	0.3	1.0	0.8	0.7	-0.7	-0.7	-0.7
Viet Nam	0.9	1.8	2.7	8.0	7.1	6.2	-5.6	-5.6	-5.6
ASEAN	**3.0**	**6.0**	**9.1**	**27.2**	**24.2**	**21.2**	**-19.0**	**-19.0**	**-19.0**
Australia	0.4	0.8	1.2	3.5	3.1	2.7	-2.4	-2.4	-2.4
China	2.1	4.3	6.4	19.2	17.0	14.9	-13.4	-13.4	-13.4
India	7.0	14.0	20.9	62.8	55.9	48.9	-44.0	-44.0	-44.0
Japan	0.9	1.8	2.8	8.3	7.4	6.4	-5.8	-5.8	-5.8
Republic of Korea	0.8	1.7	2.5	7.6	6.7	5.9	-5.3	-5.3	-5.3
New Zealand	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Other than ASEAN	**11.3**	**22.5**	**33.8**	**101.4**	**90.1**	**78.8**	**-70.9**	**-70.9**	**-70.9**
Total	**14.3**	**28.6**	**42.9**	**128.6**	**114.3**	**100.0**	**-90.0**	**-90.0**	**-90.0**

ASEAN = Association of Southeast Asian Nations, Lao PDR = Lao People's Democratic Republic, Mtoe = million tonnes of oil equivalent.

Source: Author.

Table 3.2.3 Input Energy Balance of Hydrogen, Coal and Natural Gas (2)

	Natural gas-fired									Net Natural gas demand (New + Replaced)		
	H_2 demand			Remained Natural gas			Replaced Natural gas					
	S-1 (Mtoe)	S-2 (Mtoe)	S-3 (Mtoe)	S-1 (Mtoe)	S-2 (Mtoe)	S-3 (Mtoe)	S-1 (Mtoe)	S-2 (Mtoe)	S-3 (Mtoe)	S-1 (Mtoe)	S-2 (Mtoe)	S-3 (Mtoe)
Brunei Darussalam	0.0	0.1	0.1	0.3	0.2	0.2	-0.0	-0.0	-0.0	0.1	0.1	0.0
Cambodia	0.0	0.0	0.1	0.2	0.2	0.1	-0.0	-0.0	-0.0	0.2	0.2	0.2
Indonesia	0.4	0.9	1.3	4.0	3.5	3.1	-0.4	-0.4	-0.4	13.1	11.6	10.1
Lao PDR												
Malaysia	0.3	0.7	1.0	3.0	2.7	2.3	-0.3	-0.3	-0.3	1.7	1.5	1.2
Myanmar	0.0	0.0	0.1	0.2	0.2	0.1	-0.0	-0.0	-0.0	0.6	0.6	0.5
Philippines	0.1	0.2	0.3	0.9	0.8	0.7	-0.1	-0.1	-0.1	1.6	1.4	1.2
Singapore	0.1	0.2	0.3	0.9	0.8	0.7	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1
Thailand	0.1	0.2	0.4	1.1	1.0	0.8	-0.1	-0.1	-0.1	0.8	0.7	0.6
Viet Nam	0.2	0.4	0.5	1.6	1.4	1.2	-0.2	-0.2	-0.2	7.8	6.9	6.0
ASEAN	**1.3**	**2.7**	**4.0**	**12.0**	**10.7**	**9.4**	**-1.3**	**-1.3**	**-1.3**	**25.9**	**22.8**	**19.8**
Australia	0.3	0.6	1.0	2.9	2.6	2.3	-0.3	-0.3	-0.3	3.2	2.8	2.4
China	2.7	5.4	8.1	24.4	21.7	19.0	-2.7	-2.7	-2.7	16.5	14.3	12.2
India	0.4	0.9	1.3	4.0	3.5	3.1	-0.4	-0.4	-0.4	62.4	55.4	48.4
Japan	1.1	2.1	3.2	9.6	8.5	7.5	-1.1	-1.1	-1.1	7.2	6.3	5.4
Republic of Korea	0.7	1.4	2.1	6.3	5.6	4.9	-0.7	-0.7	-0.7	6.9	6.0	5.2
New Zealand	0.0	0.1	0.1	0.3	0.2	0.2	-0.0	-0.0	-0.0	-0.0	-0.0	-0.0
Other than ASEAN	**5.3**	**10.5**	**15.8**	**47.4**	**42.2**	**36.9**	**-5.3**	**-5.3**	**-5.3**	**96.1**	**84.8**	**73.6**
Total	**6.6**	**13.2**	**19.8**	**59.5**	**52.9**	**46.3**	**-6.6**	**-6.6**	**-6.6**	**122.0**	**107.7**	**93.4**

ASEAN = Association of Southeast Asian Nations, Lao PDR = Lao People's Democratic Republic, Mtoe = million tonnes of oil equivalent.

Source: Author.

Appendix 3.3 Calculation of Hydrogen Demand Potential for Industry

Table A3.3.1 Replaced Natural Gas by Hydrogen Mixed Fuel

Country	2040 Nat gas Consumption (Mtoe)	20% of Nat gas Consumption (Mtoe)	Scenario 1 (9:1) Nat gas Consumption (Mtoe)	Scenario 1 (9:1) H_2 Consumption (Mtoe)	Scenario 2 (8:2) Nat gas Consumption (Mtoe)	Scenario 2 (8:2) H_2 Consumption (Mtoe)	Scenario 3 (7:3) Nat gas Consumption (Mtoe)	Scenario 3 (7:3) H_2 Consumption (Mtoe)
Brunei Darussalam								
Cambodia								
Indonesia	12.7	2.5	2.3	0.3	2.0	0.5	1.8	0.8
Lao PDR								
Malaysia	13.1	2.6	2.4	0.3	2.1	0.5	1.8	0.8
Myanmar	1.7	0.3	0.3	0.0	0.3	0.1	0.2	0.1
Philippines	0.8	0.2	0.1	0.0	0.1	0.0	0.1	0.0
Singapore	1.9	0.4	0.3	0.0	0.3	0.1	0.3	0.1
Thailand	9.3	1.9	1.7	0.2	1.5	0.4	1.3	0.6
Viet Nam	6.5	1.3	1.2	0.1	1.0	0.3	0.9	0.4
ASEAN	**45.9**	**9.2**	**8.3**	**0.9**	**7.3**	**1.8**	**6.4**	**2.8**
Australia	8.3	1.7	1.5	0.2	1.3	0.3	1.2	0.5
China	90.1	18.0	16.2	1.8	14.4	3.6	12.6	5.4
India	33.1	6.6	6.0	0.7	5.3	1.3	4.6	2.0
Japan	15.3	3.1	2.7	0.3	2.4	0.6	2.1	0.9
Republic of Korea	11.0	2.2	2.0	0.2	1.8	0.4	1.5	0.7
New Zealand	1.1	0.2	0.2	0.0	0.2	0.0	0.2	0.1
Other than ASEAN	**158.9**	**31.8**	**28.6**	**3.2**	**25.4**	**6.4**	**22.2**	**9.5**
Total	**204.8**	**41.0**	**36.9**	**4.1**	**32.8**	**8.2**	**28.7**	**12.3**

ASEAN = Association of Southeast Asian Nations, Lao PDR = Lao People's Democratic Republic, Mtoe = million tonnes of oil equivalent.
Source: Author.

Appendix 3.4 Calculation of Hydrogen Demand Potential for Passenger Fuel Cell Vehicle (PFCV)

Table 3.4.1 Hydrogen Demand for PFCV

Country	Gasoline demand in 2040 (Mtoe)	Ratio of Converted to H_2			Converted to H_2 (Mtoe)		
		Scenario 1	Scenario 2	Scenario 3	Scenario 1	Scenario 2	Scenario 3
Brunei Darussalam	0.6	1.0%	5.0%	10.0%	0.01	0.03	0.06
Cambodia	1.4	1.0%	5.0%	10.0%	0.01	0.07	0.14
Indonesia	73.6	1.0%	5.0%	10.0%	0.74	3.68	7.36
Lao PDR	0.3	1.0%	5.0%	10.0%	0.00	0.01	0.03
Malaysia	29.9	1.0%	5.0%	10.0%	0.30	1.49	2.99
Myanmar	11.4	1.0%	5.0%	10.0%	0.11	0.57	1.14
Philippines	6.3	1.0%	5.0%	10.0%	0.06	0.31	0.63
Singapore	0.9	1.0%	5.0%	10.0%	0.01	0.04	0.09
Thailand	8.9	1.0%	5.0%	10.0%	0.09	0.45	0.89
Viet Nam	13.1	1.0%	5.0%	10.0%	0.13	0.66	1.31
ASEAN	**146.4**				**1.46**	**7.32**	**14.64**
Australia	13.1	2.0%	10.0%	20.0%	0.26	1.31	2.61
China	250.2	1.0%	5.0%	10.0%	2.50	12.51	25.02
India	145.8	1.0%	5.0%	10.0%	1.46	7.29	14.58
Japan	26.0	2.0%	10.0%	20.0%	0.52	2.60	5.20
Republic of Korea	8.7	2.0%	10.0%	20.0%	0.17	0.87	1.74
New Zealand	2.2	2.0%	10.0%	20.0%	0.04	0.22	0.45
Other than ASEAN	**446.0**				**4.96**	**24.80**	**49.60**
Total	**592.4**				**6.42**	**32.12**	**64.24**

hydrogen demand for PFCV

'Converted to H_2 (Mtoe)'/2.7

ASEAN = Association of Southeast Asian Nations, Lao PDR = Lao People's Democratic Republic, Mtoe = million tonnes of oil equivalent, PFCV = passenger fuel cell vehicle.

Source: Author.

Appendix 3.5 Calculation of Hydrogen Demand Potential for Fuel Cell Bus (FCB)

Table 3.5.1 Hydrogen Demand for FCB

Country	Diesel demand in 2040 (Mtoe)	Ratio of Converted to H_2			Converted to H_2 (Mtoe)		
		Scenario 1	Scenario 2	Scenario 3	Scenario 1	Scenario 2	Scenario 3
Brunei Darussalam	0.3	0.025%	0.05%	0.1%	0.00	0.00	0.00
Cambodia	2.2	0.025%	0.05%	0.1%	0.00	0.00	0.00
Indonesia	84.8	0.025%	0.05%	0.1%	0.02	0.04	0.08
Lao PDR	1.2	0.025%	0.05%	0.1%	0.00	0.00	0.00
Malaysia	19.4	0.025%	0.05%	0.1%	0.00	0.01	0.02
Myanmar	0.8	0.025%	0.05%	0.1%	0.00	0.00	0.00
Philippines	12.4	0.025%	0.05%	0.1%	0.00	0.01	0.01
Singapore	1.3	0.025%	0.05%	0.1%	0.00	0.00	0.00
Thailand	18.5	0.025%	0.05%	0.1%	0.00	0.01	0.02
Viet Nam	22.8	0.025%	0.05%	0.1%	0.01	0.01	0.02
ASEAN	**163.7**				**0.04**	**0.08**	**0.16**
Australia	12.5	0.025%	0.05%	0.1%	0.00	0.01	0.01
China	180.4	0.025%	0.05%	0.1%	0.05	0.09	0.18
India	127.2	0.025%	0.05%	0.1%	0.03	0.06	0.13
Japan	15.0	0.05%	0.1%	0.2%	0.01	0.02	0.03
Republic of Korea	16.5	0.025%	0.05%	0.1%	0.00	0.01	0.02
New Zealand	1.9	0.025%	0.05%	0.1%	0.00	0.00	0.00
Other than ASEAN	**353.5**				**0.09**	**0.18**	**0.37**
Total	**517.2**				**0.13**	**0.27**	**0.53**

ASEAN = Association of Southeast Asian Nations, Lao PDR = Lao People’s Democratic Republic, Mtoe = million tonnes of oil equivalent.

Source: Author.

Appendix 3.6 Calculation of Hydrogen Demand Potential for Fuel Cell Train (FCT)

Table 3.6.1 Hydrogen Demand Potential for Fuel Cell Train

Country	Diesel demand in 2040 (Mtoe)	Share of Rail Transport	Diesel demand for Rail Transport	Ratio of Converted to H_2			Converted to H_2 (Mtoe)		
				Scenario 1	Scenario 2	Scenario 3	Scenario 1	Scenario 2	Scenario 3
Brunei Darussalam	0.3								
Cambodia	2.2	19%	0.41	5%	10%	20%	0.02	0.04	0.08
Indonesia	84.8	10%	8.48	5%	10%	20%	0.42	0.85	1.70
Lao PDR	1.2	10%	0.12	5%	10%	20%	0.01	0.01	0.02
Malaysia	19.4	10%	1.94	5%	10%	20%	0.10	0.19	0.39
Myanmar	0.8	61%	0.51	5%	10%	20%	0.03	0.05	0.10
Philippines	12.4	10%	1.24	5%	10%	20%	0.06	0.12	0.25
Singapore	1.3								
Thailand	18.5	1%	0.12	5%	10%	20%	0.01	0.01	0.02
Viet Nam	22.8	10%	2.28	5%	10%	20%	0.11	0.23	0.46
ASEAN	**163.7**		**15.10**				**0.75**	**1.51**	**3.02**
Australia	12.5	8%	1.00	5%	10%	20%	0.05	0.10	0.20
China	180.4	3%	4.72	5%	10%	20%	0.24	0.47	0.94
India	127.2	5%	6.12	5%	10%	20%	0.31	0.61	1.22
Japan	15.0	1%	0.11	5%	10%	20%	0.01	0.01	0.02
Republic of Korea	16.5	1%	0.09	5%	10%	20%	0.00	0.01	0.02
New Zealand	1.9	2%	0.04	5%	10%	20%	0.00	0.00	0.01
Other than ASEAN	**353.5**		**12.1**				**0.60**	**1.21**	**2.42**
Total	**517.2**		**27.2**				**1.36**	**2.72**	**5.44**

ASEAN = Association of Southeast Asian Nations, Lao PDR = Lao People's Democratic Republic, Mtoe = million tonnes of oil equivalent.

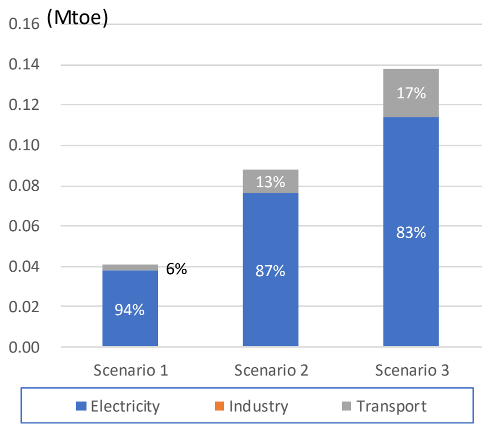
Source: Author.

Appendix 3.7 Hydrogen Demand Potential Analysis by Country

1. Brunei Darussalam

Hydrogen demand potential in Brunei Darussalam is estimated to be 0.04 Mtoe in Scenario 1, 0.09 Mtoe in Scenario 2 and 0.14 Mtoe in Scenario 3. Figure A3.7.1 shows the hydrogen demand potential by sector in Brunei Darussalam. Brunei Darussalam has no hydrogen demand potential in Industry sector.

Figure A3.7.1 Hydrogen Demand Potential by Sector (Brunei Darussalam)

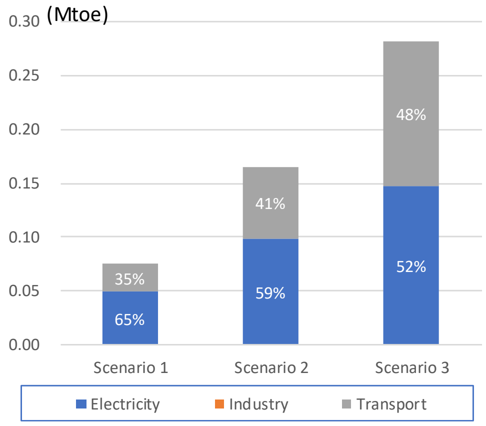


Mtoe = million tonnes of oil equivalent.
Source: Author.

2. Cambodia

Hydrogen demand potential in Cambodia is estimated to be 0.07 Mtoe in Scenario 1, 0.17 Mtoe in Scenario 2 and 0.28 Mtoe in Scenario 3. Figure A3.7.2 shows the hydrogen demand potential by sector in Cambodia. Cambodia has no potential in Industry sector.

Figure A3.7.2 Hydrogen Demand Potential by Sector (Cambodia)

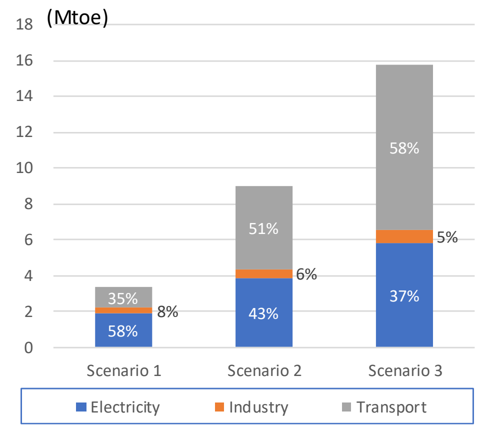


Mtoe = million tonnes of oil equivalent.
Source: Author.

3. Indonesia

Hydrogen demand potential in Indonesia is estimated to be 2.9 Mtoe in Scenario 1, 6.6 Mtoe in Scenario 2, and 11.1 Mtoe in Scenario 3. Indonesia has the largest potential in ASEAN and the third-largest potential in the East Asia Summit (EAS) region. Figure A3.7.3 shows the hydrogen demand potential by sector of Indonesia.

Figure A3.7.3 Hydrogen Demand Potential by Sector (Indonesia)

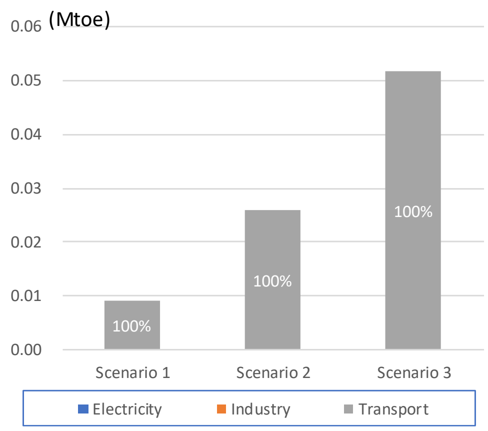


Mtoe = million tonnes of oil equivalent.
Source: Author.

4. Lao PDR

Hydrogen demand potential in Lao PDR is estimated to be 0.01 Mtoe in Scenario 1, 0.03 Mtoe in Scenario 2, and 0.05 Mtoe in Scenario 3. The following figure shows the hydrogen demand potential by sector in Lao PDR. Lao PDR has no demand potential in electricity generation sector and industry because, with no plan to introduce natural gas in the energy mix, there is no replacement target.

Figure A3.7.4 Hydrogen Demand Potential by Sector (Lao PDR)



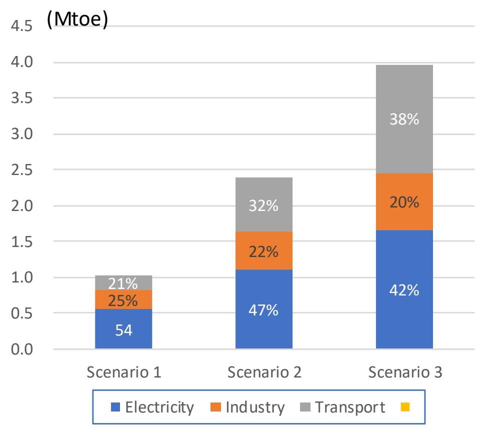
Mtoe = million tonnes of oil equivalent.

Source: Author.

5. Malaysia

Hydrogen demand potential in Malaysia is estimated to be 1.0 Mtoe in Scenario 1, 2.4 Mtoe in Scenario 2, and 4.0 Mtoe in Scenario 3. In ASEAN, Malaysia has the third-largest potential in all Scenarios. Figure A3.7.5 shows the hydrogen demand potential by sector in Malaysia.

Figure A3.7.5 Hydrogen Demand Potential by Sector (Malaysia)



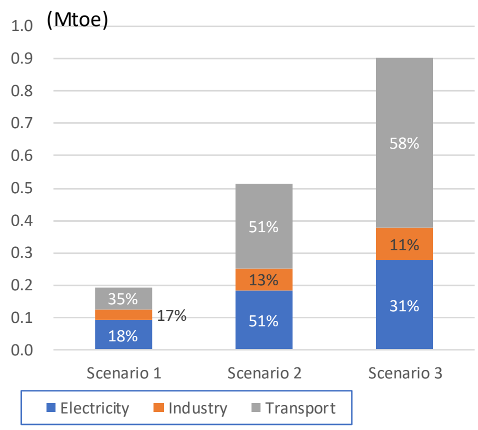
Mtoe = million tonnes of oil equivalent.

Source: Author.

6. Myanmar

Hydrogen demand potential in Myanmar is estimated to be 0.2 Mtoe in Scenario 1, 0.5 Mtoe in Scenario 2, and 0.9 Mtoe in Scenario 3. Figure A3.7.6 shows the hydrogen demand potential by sector in Myanmar. A feature of Myanmar's potential is that the transport sector share is higher than in other ASEAN countries.

Figure A3.7.6 Hydrogen Demand Potential by Sector (Myanmar)

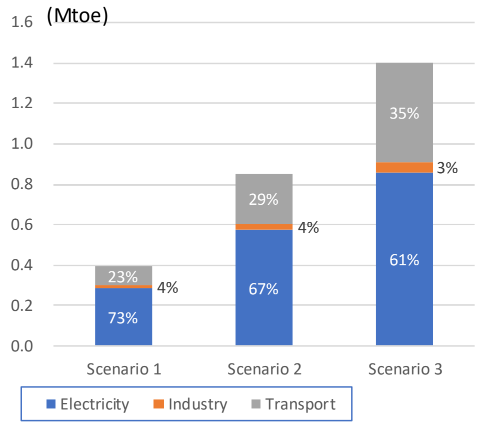


Mtoe = million tonnes of oil equivalent.
Source: Author.

7. Philippines

Hydrogen demand potential in Philippines is estimated to be 0.4 Mtoe in Scenario 1, 0.9 Mtoe in Scenario 2, and 1.4 Mtoe in Scenario 3. Figure A3.7.7 shows the hydrogen demand potential by sector in Philippines.

Figure A3.7.7 Hydrogen Demand Potential by Sector (Philippines)

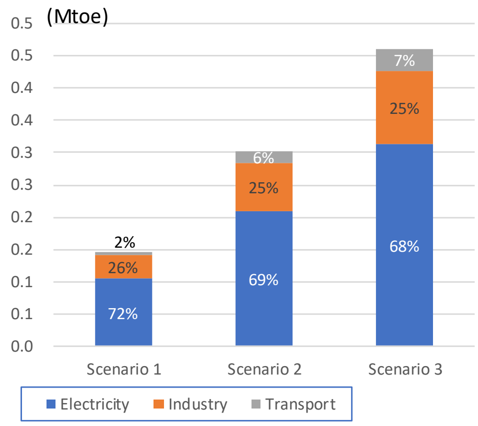


Mtoe = million tonnes of oil equivalent.
Source: Author.

8. Singapore

Hydrogen demand potential in Singapore is estimated to be 0.1 Mtoe in Scenario 1, 0.3 Mtoe in Scenario 2, and 0.5 Mtoe in Scenario 3. Figure A3.7.8 shows the hydrogen demand potential by sector in Singapore.

Figure A3.7.8 Hydrogen Demand Potential by Sector (Singapore)

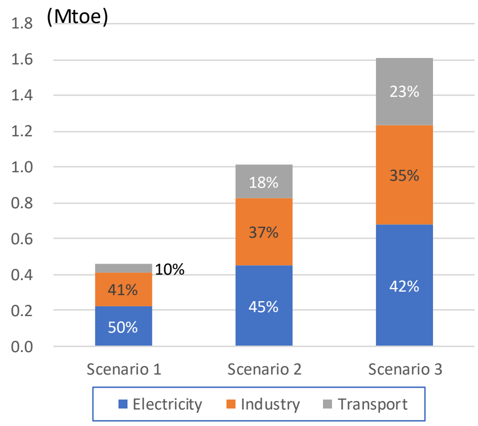


Mtoe = million tonnes of oil equivalent.
Source: Author.

9. Thailand

Hydrogen demand potential in Thailand is estimated to be 0.5 Mtoe in Scenario 1, 1.0 Mtoe in Scenario 2, and 1.6 Mtoe in Scenario 3. Figure A3.7.9 shows the hydrogen demand potential by sector in Thailand.

Figure A3.7.9 Hydrogen Demand Potential by Sector (Thailand)

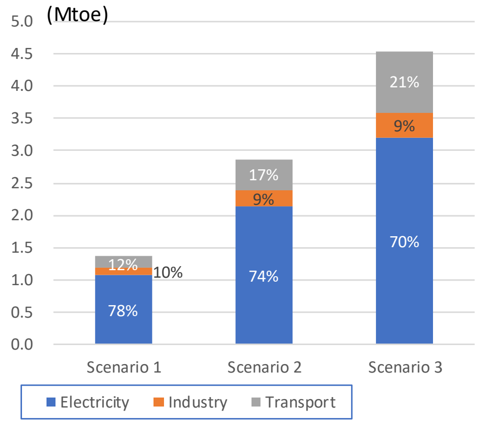


Mtoe = million tonnes of oil equivalent.
Source: Author.

10. Viet Nam

Hydrogen demand potential in Viet Nam is estimated to be 1.4 Mtoe in Scenario 1, 2.9 Mtoe in Scenario 2, and 4.6 Mtoe in Scenario 3. In ASEAN, Viet Nam has the second-largest potential in all Scenarios. Figure A3.7.10 shows the hydrogen demand potential by sector in Viet Nam.

Figure A3.7.10 Hydrogen Demand Potential by Sector (Viet Nam)

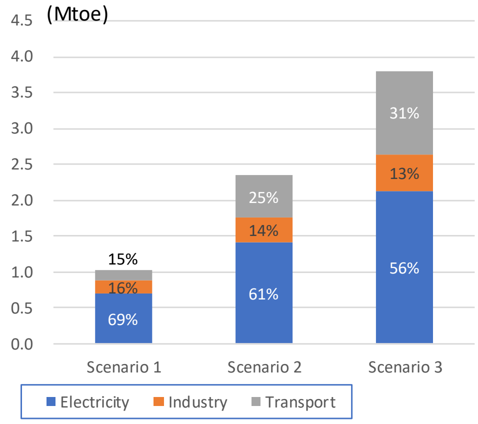


Mtoe = million tonnes of oil equivalent.
Source: Author.

11. Australia

Hydrogen demand potential in Australia is estimated to be 1.0 Mtoe in Scenario 1, 2.3 Mtoe in Scenario 2, and 3.8 Mtoe in Scenario 3. Figure A3.7.11 shows the hydrogen demand potential by sector in Australia.

Figure A3.7.11 Hydrogen Demand Potential by Sector (Australia)

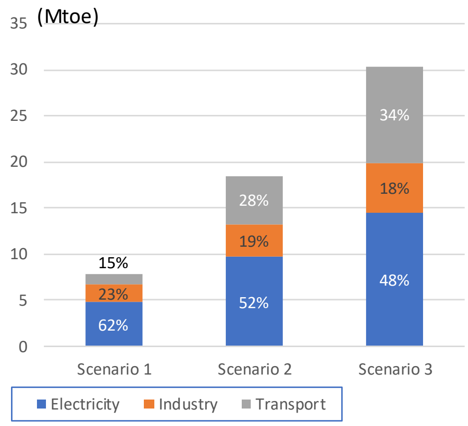


Mtoe = million tonnes of oil equivalent.
Source: Author.

12. China

Hydrogen demand potential in China is estimated to be 7.9 Mtoe in Scenario 1, 18.5 Mtoe in Scenario 2, and 30.3 Mtoe in Scenario 3. In EAS, China has the second-largest potential in all Scenarios. Figure A3.7.12 shows the hydrogen demand potential by sector in China.

Figure A3.7.12 Hydrogen Demand Potential by Sector (China)

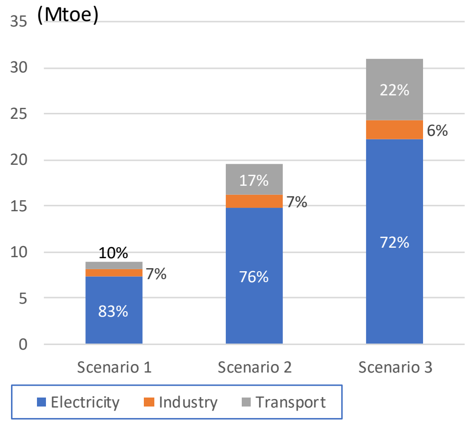


Mtoe = million tonnes of oil equivalent.
Source: Author.

13. India

Hydrogen demand potential in India is estimated to be 9.0 Mtoe in Scenario 1, 19.5 Mtoe in Scenario 2, and 31.0 Mtoe in Scenario 3. In EAS, India has the largest potential in all Scenarios. Figure A3.7.13 shows the hydrogen demand potential by sector in India.

Figure A3.7.13 Hydrogen Demand Potential by Sector (India)

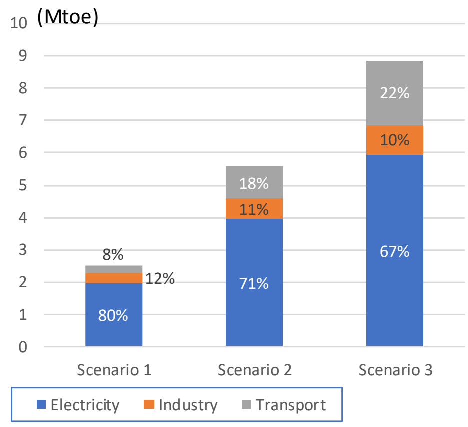


Mtoe = million tonnes of oil equivalent.
Source: Author.

14. Japan

Hydrogen demand potential in Japan is estimated to be 2.5 Mtoe in Scenario 1, 5.6 Mtoe in Scenario 2, and 8.9 Mtoe in Scenario 3. In EAS, Japan has the fourth-largest hydrogen demand potential. Figure A3.7.14 shows the hydrogen demand potential by sector in Japan.

Figure A3.7.14 Hydrogen Demand Potential by Sector (Japan)

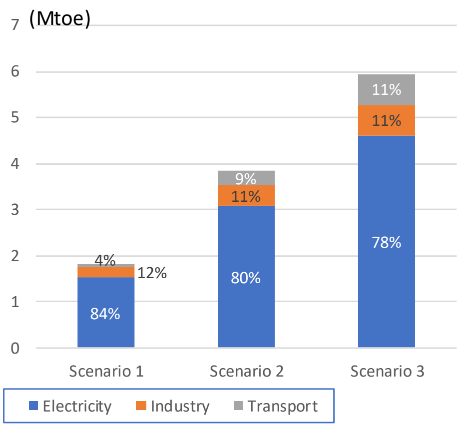


Mtoe = million tonnes of oil equivalent.
Source: Author.

15. Republic of Korea

Hydrogen demand potential in Republic of Korea (henceforth Korea) is estimated to be 1.8 Mtoe in Scenario 1, 3.9 Mtoe in Scenario 2, and 6.0 Mtoe in Scenario 3. In EAS, Korea has the fifth-largest hydrogen demand potential. Figure A3.7.15 shows the hydrogen demand potential by sector in Korea.

Figure A3.7.15 Hydrogen Demand Potential by Sector (Republic of Korea)

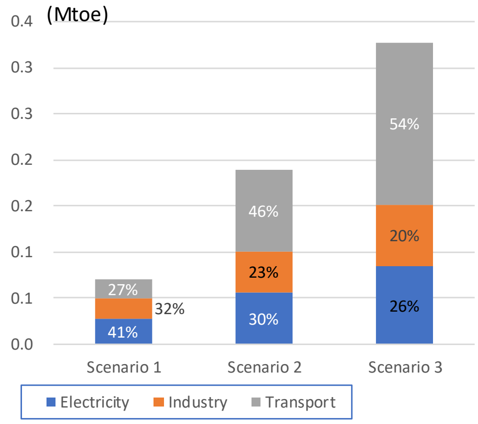


Mtoe = million tonnes of oil equivalent.
Source: Author.

16. New Zealand

Hydrogen demand potential in New Zealand is estimated to be 0.1 Mtoe in Scenario 1, 0.2 Mtoe in Scenario 2, and 0.3 Mtoe in Scenario 3. Figure A3.7.16 shows the hydrogen demand potential by sector in New Zealand. A feature of New Zealand's potential is that the share of the transport sector is higher than other many countries.

Figure A3.7.16 Hydrogen Demand Potential by Sector (New Zealand)



Mtoe = million tonnes of oil equivalent.
Source: Author.

Appendix 3.8: Impact for Coal and Natural Gas in Electricity Generation Sector

Table A3.8.1 shows the impact for coal and natural gas. Coal is replaced by hydrogen. Natural gas is not necessarily replaced by hydrogen, because replaced coal is converted to hydrogen and natural gas. Natural gas demand increases in many countries.

Table A3.8.1 Impact for Coal and Natural Gas in Electricity Generation Sector

Country	Replaced Coal (million tonnes)			Net Natural gas demand (Bcm)		
	Scenario 1	Scenario 2	Scenario 3	Scenario 1	Scenario 2	Scenario 3
Brunei Darussalam	-0.1	-0.1	-0.1	0.1	0.1	0.0
Cambodia	-0.3	-0.3	-0.3	0.3	0.2	0.2
Indonesia	-15.4	-15.4	-15.4	13.7	12.1	10.6
Lao PDR						
Malaysia	-2.3	-2.3	-2.3	1.8	1.5	1.3
Myanmar	-0.7	-0.7	-0.7	0.7	0.6	0.5
Philippines	-1.9	-1.9	-1.9	1.7	1.5	1.3
Singapore	-0.0	-0.0	-0.0	-0.1	-0.1	-0.1
Thailand	-1.1	-1.1	-1.1	0.9	0.8	0.7
Viet Nam	-9.1	-9.1	-9.1	8.2	7.3	6.3
ASEAN	**-31.0**	**-31.0**	**-31.0**	**27.1**	**23.9**	**20.8**
Australia	-4.0	-4.0	-4.0	3.3	2.9	2.5
China	-21.9	-21.9	-21.9	17.2	15.0	12.8
India	-71.7	-71.7	-71.7	65.3	58.0	50.7
Japan	-9.5	-9.5	-9.5	7.6	6.6	5.6
Republic of Korea	-8.6	-8.6	-8.6	7.2	6.3	5.4
New Zealand	0.0	0.0	0.0	-0.0	-0.0	-0.0
Other than ASEAN	**-115.6**	**-115.6**	**-115.6**	**100.6**	**88.8**	**77.0**
Total	**-146.6**	**-146.6**	**-146.6**	**127.7**	**112.7**	**97.8**

ASEAN = Association of Southeast Asian Nations, Lao PDR = Lao People's Democratic Republic.
Note: Net Calorific Value of Coal = 0.6183 toe/tonne (Australian export bituminous coal, IEA)
1 toe = 1.047 * 1,000 cubic metre of Natural gas. The same applies hereafter.
Source: Author.

Appendix 3.9: CO_2 Emissions from Replaced Electricity Generation

Table A3.9.1 CO_2 Emissions from Replaced Electricity Generation

Country	Coal (million tonnes)				Natural gas (million tonnes)			
		Scenario 1	Scenario 2	Scenario 3		Scenario 1	Scenario 2	Scenario 3
	Coal 100%	Gas 90%	Gas 80%	Gas 70%	Gas 100%	Gas 90%	Gas 80%	Gas 70%
Brunei Darussalam	0.5	0.2	0.2	0.2	0.7	0.6	0.5	0.5
Cambodia	1.4	0.6	0.6	0.5	0.4	0.4	0.4	0.3
Indonesia	68.2	31.8	28.3	24.7	10.3	9.3	8.3	7.2
Lao PDR								
Malaysia	10.2	4.8	4.2	3.7	7.8	7.0	6.2	5.5
Myanmar	3.3	1.5	1.4	1.2	0.5	0.4	0.4	0.3
Philippines	8.5	3.9	3.5	3.1	2.4	2.1	1.9	1.7
Singapore	0.1	0.0	0.0	0.0	2.4	2.2	1.9	1.7
Thailand	4.8	2.2	2.0	1.7	2.8	2.5	2.3	2.0
Viet Nam	40.3	18.8	16.7	14.6	4.1	3.7	3.3	2.9
ASEAN	**137.2**	**63.9**	**56.8**	**49.7**	**31.4**	**28.3**	**25.2**	**22.0**
Australia	17.5	8.2	7.3	6.4	7.6	6.8	6.1	5.3
China	96.6	45.0	40.0	35.0	63.8	57.4	51.0	44.6
India	316.8	147.6	131.2	114.8	10.4	9.4	8.3	7.3
Japan	41.8	19.5	17.3	15.1	25.0	22.5	20.0	17.5
Republic of Korea	38.2	17.8	15.8	13.9	16.4	14.8	13.1	11.5
New Zealand	0.0	0.0	0.0	0.0	0.7	0.6	0.5	0.5
Other than ASEAN	**511.0**	**238.1**	**211.6**	**185.2**	**123.9**	**111.5**	**99.1**	**86.7**
Total	**648.2**	**302.0**	**268.5**	**234.9**	**155.3**	**139.8**	**124.2**	**108.7**

ASEAN = Association of Southeast Asian Nations, Lao PDR = Lao People's Democratic Republic.

Note: CO_2 factor: Bituminous coal = 3.961 tonne-CO_2/toe, Natural gas = 2.349 tonne-CO_2/toe.

Source: Author.

Table 3.9.2 CO_2 Emissions Reduction in Electricity Generation Sector

Country	Coal-fired			Natural gas-fired			Total		
	Scenario 1 (million tonnes)	Scenario 2 (million tonnes)	Scenario 3 (million tonnes)	Scenario 1 (million tonnes)	Scenario 2 (million tonnes)	Scenario 3 (million tonnes)	Scenario 1 (million tonnes)	Scenario 2 (million tonnes)	Scenario 3 (million tonnes)
Brunei Darussalam	0.2	0.3	0.3	0.1	0.1	0.2	0.3	0.4	0.5
Cambodia	0.7	0.8	0.9	0.0	0.1	0.1	0.8	0.9	1.0
Indonesia	36.4	40.0	43.5	1.0	2.1	3.1	37.5	42.0	46.6
Lao PDR									
Malaysia	5.4	6.0	6.5	0.8	1.6	2.3	6.2	7.5	8.8
Myanmar	1.8	1.9	2.1	0.0	0.1	0.1	1.8	2.0	2.2
Philippines	4.5	5.0	5.4	0.2	0.5	0.7	4.8	5.4	6.1
Singapore	0.0	0.0	0.0	0.2	0.5	0.7	0.3	0.5	0.8
Thailand	2.6	2.8	3.1	0.3	0.6	0.8	2.9	3.4	3.9
Viet Nam	21.5	23.6	25.7	0.4	0.8	1.2	21.9	24.4	26.9
ASEAN	**73.3**	**80.4**	**87.5**	**3.1**	**6.3**	**9.4**	**76.4**	**86.7**	**96.9**
Australia	9.4	10.3	11.2	0.8	1.5	2.3	10.1	11.8	13.5
China	51.6	56.6	61.6	6.4	12.8	19.1	58.0	69.4	80.7
India	169.2	185.6	202.0	1.0	2.1	3.1	170.2	187.7	205.1
Japan	22.3	24.5	26.7	2.5	5.0	7.5	24.8	29.5	34.2
Republic of Korea	20.4	22.4	24.4	1.6	3.3	4.9	22.1	25.7	29.3
New Zealand	0.0	0.0	0.0	0.1	0.1	0.2	0.1	0.1	0.2
Other than ASEAN	**272.9**	**299.4**	**325.8**	**12.4**	**24.8**	**37.2**	**285.3**	**324.1**	**363.0**
Total	**346.2**	**379.7**	**413.3**	**15.5**	**31.1**	**46.6**	**361.7**	**410.8**	**459.9**

ASEAN = Association of Southeast Asian Nations, Lao PDR = Lao People's Democratic Republic.

Note: CO_2 factor: Bituminous coal = 3.961 tonne-CO_2/toe, Natural gas = 2.349 tonne-CO_2/toe.

Source: Author.

Appendix 3.10. Replaced Energy by Hydrogen in Industry Sector

Table A3.10.1 Replaced Natural Gas by Hydrogen in Industry sector in 2040(in Bcm)

Country	Scenario 1	Scenario 2	Scenario 3
Brunei Darussalam			
Cambodia			
Indonesia	-0.3	-0.5	-0.8
Lao PDR			
Malaysia	-0.3	-0.5	-0.8
Myanmar	-0.0	-0.1	-0.1
Philippines	-0.0	-0.0	-0.0
Singapore	-0.0	-0.1	-0.1
Thailand	-0.2	-0.4	-0.6
Viet Nam	-0.1	-0.3	-0.4
ASEAN	**-1.0**	**-1.9**	**-2.9**
Australia	-0.2	-0.3	-0.5
China	-1.9	-3.8	-5.7
India	-0.7	-1.4	-2.1
Japan	-0.3	-0.6	-1.0
Republic of Korea	-0.2	-0.5	-0.7
New Zealand	-0.0	-0.0	-0.1
Other than ASEAN	**-3.3**	**-6.7**	**-10.0**
Total	**-4.3**	**-8.6**	**-12.9**

ASEAN = Association of Southeast Asian Nations, Lao PDR = Lao People's Democratic Republic.
Source: Author.

Appendix 3.11. CO_2 Emissions in Industry Sector

Table A3.11.1 CO_2 Emissions from Replaced Natural Gas in Industry

Country	Gas 100%	Scenario 1 Gas 90%	Scenario 2 Gas 80%	Scenario 3 Gas 70%
Brunei Darussalam				
Cambodia				
Indonesia	6.0	5.4	4.8	4.2
Lao PDR				
Malaysia	6.1	5.5	4.9	4.3
Myanmar	0.8	0.7	0.6	0.5
Philippines	0.4	0.3	0.3	0.3
Singapore	0.9	0.8	0.7	0.6
Thailand	4.4	3.9	3.5	3.1
Viet Nam	3.1	2.8	2.5	2.1
ASEAN	**21.6**	**19.4**	**17.3**	**15.1**
Australia	3.9	3.5	3.1	2.7
China	42.3	38.1	33.8	29.6
India	15.6	14.0	12.4	10.9
Japan	7.2	6.5	5.7	5.0
Republic of Korea	5.2	4.6	4.1	3.6
New Zealand	0.5	0.5	0.4	0.4
Other than ASEAN	**74.7**	**67.2**	**59.7**	**52.3**
Total	**96.2**	**86.6**	**77.0**	**67.4**

Table A3.11.2 CO_2 Emissions Reduction

Country	Scenario 1 (million tonnes)	Scenario 2 (million tonnes)	Scenario 3 (million tonnes)
Brunei Darussalam			
Cambodia			
Indonesia	0.6	1.2	1.8
Lao PDR			
Malaysia	0.6	1.2	1.8
Myanmar	0.1	0.2	0.2
Philippines	0.0	0.1	0.1
Singapore	0.1	0.2	0.3
Thailand	0.4	0.9	1.3
Viet Nam	0.3	0.6	0.9
ASEAN	**2.2**	**4.3**	**6.5**
Australia	0.4	0.8	1.2
China	4.2	8.5	12.7
India	1.6	3.1	4.7
Japan	0.7	1.4	2.2
Republic of Korea	0.5	1.0	1.5
New Zealand	0.1	0.1	0.2
Other than ASEAN	**7.5**	**14.9**	**22.4**
Total	**9.6**	**19.2**	**28.9**

ASEAN = Association of Southeast Asian Nations, Lao PDR = Lao People's Democratic Republic.
Note: CO_2 factor: Natural gas = 2.349 tonne-CO_2/toe.
Source: Author.

Appendix 3.12. Replaced Energy by Hydrogen in Transport Sector

1. Gasoline

Table A3.12.1 Replaced Gasoline Demand by Hydrogen in Transport Sector in 2040(in thousand tonnes)

Country	Scenario 1 PFCV	Scenario 2 PFCV	Scenario 3 PFCV
Brunei Darussalam	-6	-30	-59
Cambodia	-13	-66	-132
Indonesia	-691	-3,455	-6,909
Lao PDR	-2	-12	-24
Malaysia	-281	-1,403	-2,806
Myanmar	-107	-536	-1,072
Philippines	-59	-295	-590
Singapore	-8	-42	-84
Thailand	-84	-418	-837
Viet Nam	-123	-615	-1,230
ASEAN	**-1,374**	**-6,871**	**-13,743**
Australia	-245	-1,225	-2,450
China	-2,349	-11,745	-23,490
India	-1,369	-6,844	-13,689
Japan	-489	-2,443	-4,885
Republic of Korea	-163	-814	-1,629
New Zealand	-42	-210	-419
Other than ASEAN	**-4,656**	**-23,281**	**-46,562**
Total	**-6,031**	**-30,153**	**-60,305**

ASEAN = Association of Southeast Asian Nations, Lao PDR = Lao People's Democratic Republic, PFCV = passenger fuel cell vehicle.

Note: Net Calorific Value of Gasoline = 1.0653 toe/tonne (Japan, IEA). The same applies hereafter.

Source: Author.

2. Diesel

Table A3.12.2 Replaced Diesel Demand by Hydrogen in FCB and FCT sector in 2040

(in thousand tonnes)

Country	Scenario 1			Scenario 2			Scenario 3		
	FCB	FCT	Total	FCB	FCT	Total	FCB	FCT	Total
Brunei Darussalam	-0		-0	-0		-0	-0		-0
Cambodia	-1	-20	-20	-1	-40	-41	-2	-80	-82
Indonesia	-21	-417	-437	-42	-833	-875	-83	-1,667	-1,750
Lao PDR	-0	-6	-6	-1	-12	-13	-1	-24	-26
Malaysia	-5	-95	-100	-10	-190	-200	-19	-380	-399
Myanmar	-0	-25	-25	-0	-50	-50	-1	-100	-100
Philippines	-3	-61	-64	-6	-122	-128	-12	-245	-257
Singapore	-0		-0	-1		-1	-1		-1
Thailand	-5	-6	-11	-9	-12	-21	-18	-24	-42
Viet Nam	-6	-112	-118	-11	-224	-235	-22	-448	-470
ASEAN	**-40**	**-742**	**-782**	**-80**	**-1,484**	**-1,564**	**-161**	**-2,967**	**-3,128**
Australia	-3	-49	-52	-6	-98	-105	-12	-197	-209
China	-44	-232	-276	-89	-464	-553	-177	-928	-1,106
India	-31	-301	-332	-63	-601	-664	-125	-1,202	-1,327
Japan	-7	-5	-13	-15	-11	-26	-30	-22	-51
Republic of Korea	-4	-4	-9	-8	-9	-17	-16	-18	-34
New Zealand	-0	-2	-3	-1	-4	-5	-2	-8	-10
Other than ASEAN	**-91**	**-594**	**-684**	**-181**	**-1,188**	**-1,369**	**-362**	**-2,375**	**-2,737**
Total	**-131**	**-1,336**	**-1,466**	**-262**	**-2,671**	**-2,933**	**-523**	**-5,343**	**-5,866**

ASEAN = Association of Southeast Asian Nations, FCB = fuel cell bus, FCT = fuel cell train, Lao PDR = Lao People’s Democratic Republic.
Note: Net Calorific Value of Diesel = 1.0175 toe/tonne (Japan, IEA).
Source: Author.

Appendix 3.13 Hydrogen Demand and Replaced Diesel by Hydrogen

Table A3.13.1 Replaced Diesel by Hydrogen

Country	H_2 demand (Mtoe)			Replaced Diesel (thousand tonnes)		
	Scenario 1	Scenario 2	Scenario 3	Scenario 1	Scenario 2	Scenario 3
Brunei Darussalam						
Cambodia	0.02	0.04	0.08	-20	-40	-80
Indonesia	0.42	0.85	1.70	-417	-833	-1,667
Lao PDR	0.01	0.01	0.02	-6	-12	-24
Malaysia	0.10	0.19	0.39	-95	-190	-380
Myanmar	0.03	0.05	0.10	-25	-50	-100
Philippines	0.06	0.12	0.25	-61	-122	-245
Singapore				0	0	0
Thailand	0.01	0.01	0.02	-6	-12	-24
Viet Nam	0.11	0.23	0.46	-112	-224	-448
ASEAN	**0.75**	**1.51**	**3.02**	**-742**	**-1,484**	**-2,967**
Australia	0.05	0.10	0.20	-49	-98	-197
China	0.24	0.47	0.94	-232	-464	-928
India	0.31	0.61	1.22	-301	-601	-1,202
Japan	0.01	0.01	0.02	-5	-11	-22
Republic of Korea	0.00	0.01	0.02	-4	-9	-18
New Zealand	0.00	0.00	0.01	-2	-4	-8
Other than ASEAN	**0.60**	**1.21**	**2.42**	**-594**	**-1,188**	**-2,375**
Total	**1.36**	**2.72**	**5.44**	**-1,336**	**-2,671**	**-5,343**

Table A3.13.2 CO_2 Emissions from Replaced Diesel

Country	Scenario 1 (million tonnes)	Scenario 2 (million tonnes)	Scenario 3 (million tonnes)
Brunei Darussalam			
Cambodia	0.1	0.1	0.3
Indonesia	1.3	2.6	5.3
Lao PDR	0.0	0.0	0.1
Malaysia	0.3	0.6	1.2
Myanmar	0.1	0.2	0.3
Philippines	0.2	0.4	0.8
Singapore			
Thailand	0.0	0.0	0.1
Viet Nam	0.4	0.7	1.4
ASEAN	**2.3**	**4.7**	**9.4**
Australia	0.2	0.3	0.6
China	0.7	1.5	2.9
India	0.9	1.9	3.8
Japan	0.0	0.0	0.1
Republic of Korea	0.0	0.0	0.1
New Zealand	0.0	0.0	0.0
Other than ASEAN	**1.9**	**3.7**	**7.5**
Total	**4.2**	**8.4**	**16.9**

ASEAN = Association of Southeast Asian Nations, Lao PDR = Lao People's Democratic Republic, Mtoe = million tonnes of oil equivalent.
Source: Author.

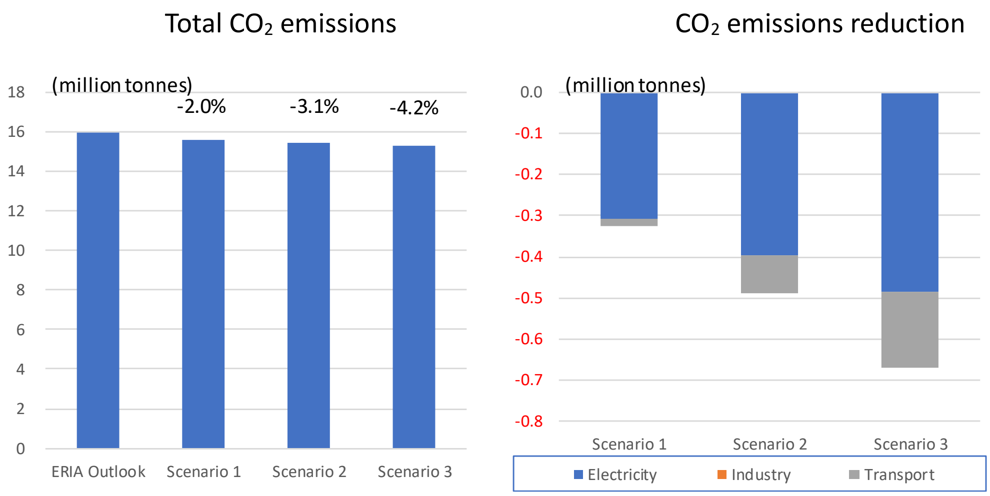
Appendix 3.14 CO_2 Emissions Reduction Analysis by Country

1. Brunei Darussalam

Total CO_2 emissions reduction in Brunei Darussalam reaches 0.3 million tonnes in Scenario 1, 0.5 million tonnes in Scenario 2, and 0.7 million tonnes in Scenario 3.

Figure A3.14.1 shows the total CO_2 emissions from fuel combustion and emissions reduction by sector in Brunei Darussalam. There is no CO_2 emissions reduction from the transport sector in Brunei Darussalam.

Figure A3.14.1 CO_2 Emissions Reduction (Brunei Darussalam)



ERIA = Economic Research Institute for ASEAN and East Asia.

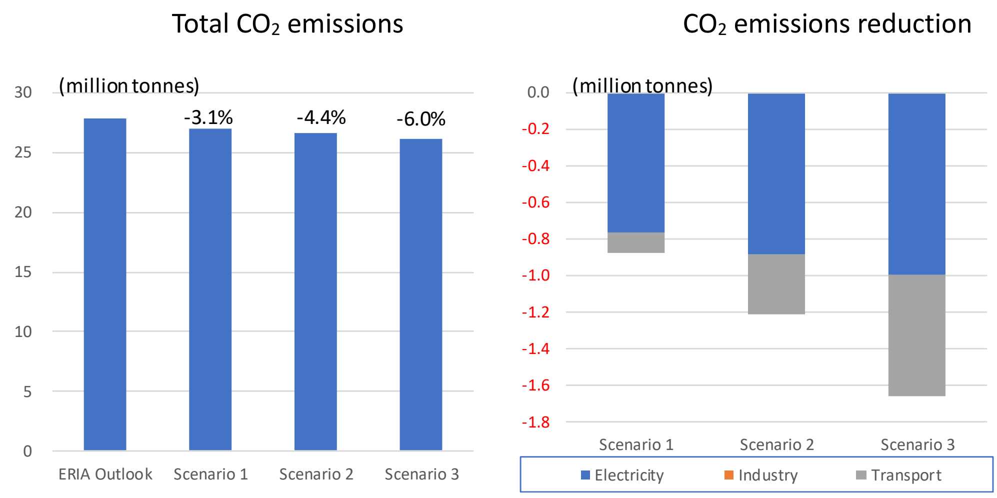
Source: Author.

2. Cambodia

CO_2 emissions reduction in Cambodia reaches 0.9 million tonnes in Scenario 1, 1.2 million tonnes in Scenario 2, and 1.7 million tonnes in Scenario 3.

Figure A3.14.2 shows the total CO_2 emissions from fuel combustion and CO_2 emissions reduction by sector in Cambodia. There is no CO_2 emissions reduction from the industry sector in Cambodia.

Figure A3.14.2 CO_2 Emissions Reduction (Cambodia)



ERIA = Economic Research Institute for ASEAN and East Asia.

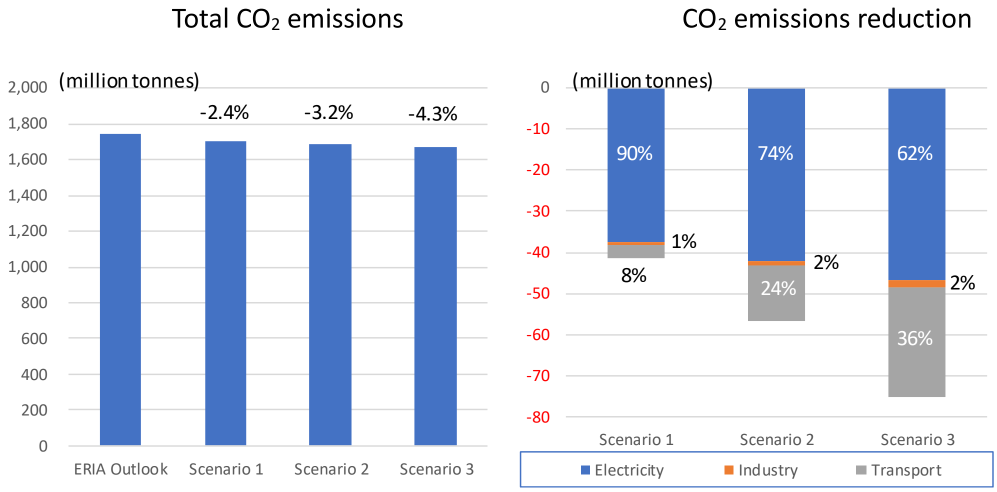
Source: Author.

3. Indonesia

CO_2 emissions reduction in Indonesia reaches 41.6 million tonnes in Scenario 1, 56.7 million tonnes in Scenario 2, and 75.3 million tonnes in Scenario 3. Indonesia has a large CO_2 emissions reduction potential with a higher share of coal-fired electricity generation because 20% of coal-fired new electricity generation is assumed to be converted to hydrogen and natural gas mixed fuel, which emits less CO_2 than coal. Indonesia has the largest CO_2 reduction potential in ASEAN and the third-largest CO_2 reduction potential in EAS.

Figure A3.14.3 shows the total CO_2 emissions from fuel combustion and CO_2 emissions reduction by sector in Indonesia.

Figure A3.14.3 CO_2 Emissions Reduction (Indonesia)



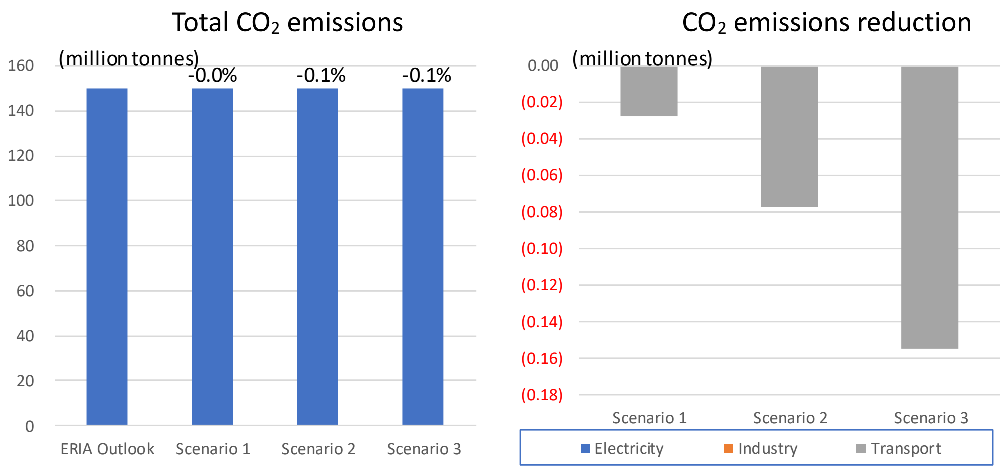
ERIA = Economic Research Institute for ASEAN and East Asia.
Source: Author.

4. Lao PDR

CO_2 emissions reduction in Lao PDR reaches 41.6 million tonnes in Scenario 1, 56.7 million tonnes in Scenario 2, and 75.3 million tonnes in Scenario 3.

Figure A3.14.4 shows the total CO_2 emissions from fuel combustion and CO_2 emissions reduction by sector in Lao PDR. There is no CO_2 emissions reduction from the electricity generation and industry sectors in Lao PDR.

Figure A3.14.4 CO_2 Emissions Reduction (Lao PDR)



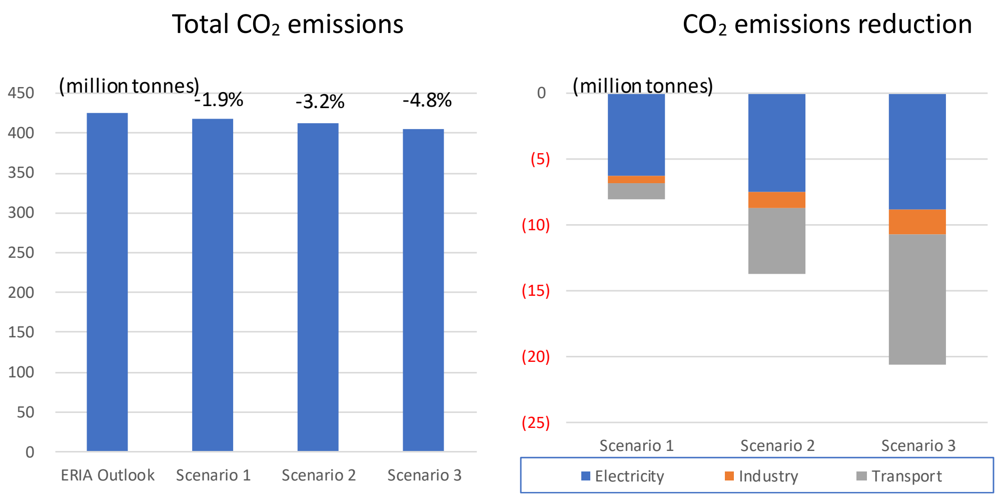
ERIA = Economic Research Institute for ASEAN and East Asia.
Source: Author.

5. Malaysia

CO_2 emissions reduction in Malaysia reaches 8.0 million tonnes in Scenario 1, 13.7 million tonnes in Scenario 2 and 20.6 million tonnes in Scenario 3.

Figure A3.14.5 shows the total CO_2 emissions from fuel combustion and CO_2 emissions reduction by sector in Malaysia.

Figure A3.14.5 CO_2 Emissions Reduction (Malaysia)



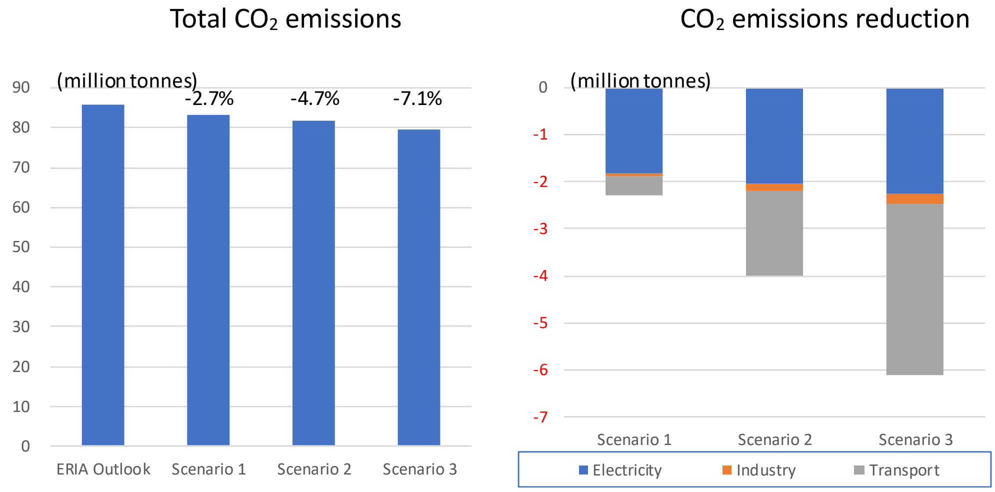
ERIA = Economic Research Institute for ASEAN and East Asia.
Source: Author.

6. Myanmar

CO_2 emissions reduction in Myanmar reaches 2.3 million tonnes in Scenario 1, 4.0 million tonnes in Scenario 2, and 6.1 million tonnes in Scenario 3.

Figure A3.14.6 shows the total CO_2 emissions from fuel combustion and CO_2 emissions reduction by sector in Myanmar.

Figure A3.14.6 CO_2 Emissions Reduction (Myanmar)



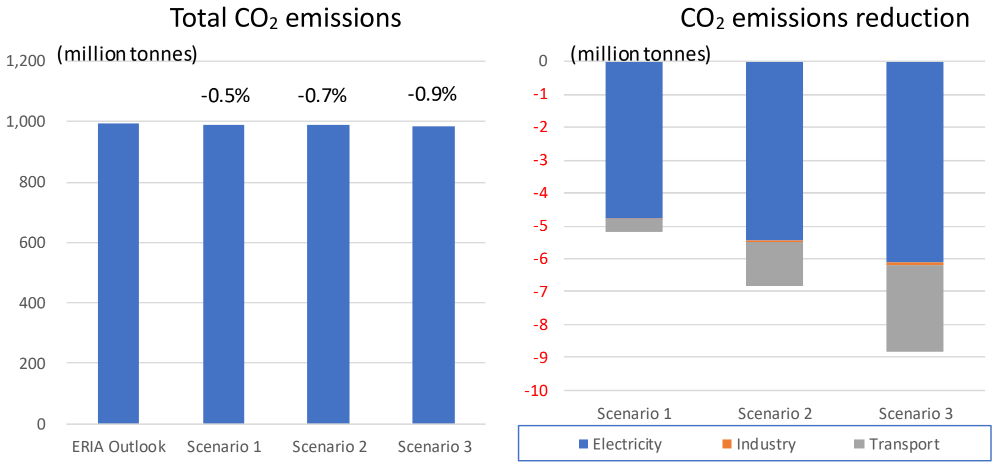
ERIA = Economic Research Institute for ASEAN and East Asia.
Source: Author.

7. Philippines

CO_2 emissions reduction in the Philippines reaches 5.2 million tonnes in Scenario 1, 6.8 million tonnes in Scenario 2, and 8.8 million tonnes in Scenario 3.

Figure A3.14.7 shows the total CO_2 emissions from fuel combustion and CO_2 emissions reduction by sector in the Philippines.

Figure A3.14.7 CO_2 Emissions Reduction (Philippines)



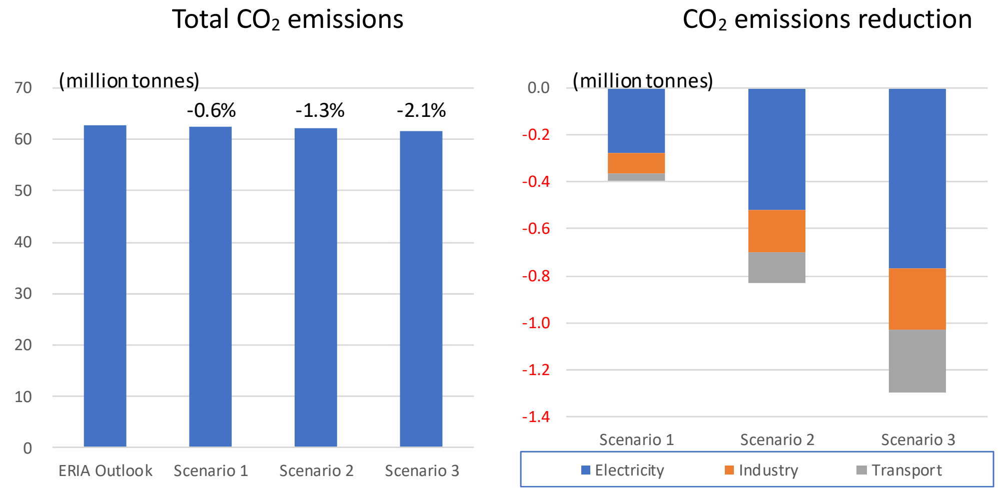
ERIA = Economic Research Institute for ASEAN and East Asia.
Source: Author.

8. Singapore

CO_2 emissions reduction in Singapore reaches 0.4 million tonnes in Scenario 1, 0.8 million tonnes in Scenario 2, and 1.3 million tonnes in Scenario 3.

Figure A3.14.8 shows the total CO_2 emissions from fuel combustion and CO_2 emissions reduction by sector in Singapore.

Figure A3.14.8 CO_2 Emissions Reduction (Singapore)



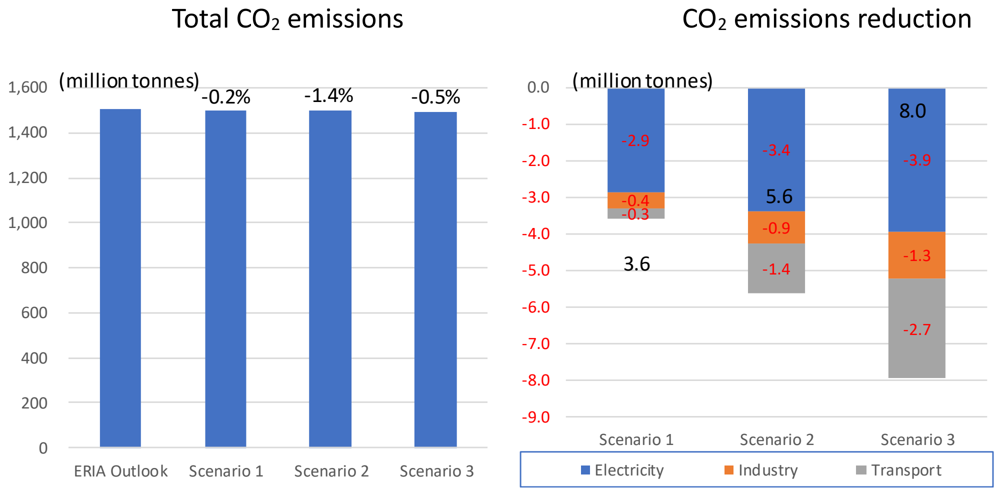
ERIA = Economic Research Institute for ASEAN and East Asia.
Source: Author.

9. Thailand

CO_2 emissions reduction in Thailand reaches 0.4 million tonnes in Scenario 1, 0.8 million tonnes in Scenario 2, and 1.3 million tonnes in Scenario 3.

Figure A3.14.9 shows the total CO_2 emissions from fuel combustion and CO_2 emissions reduction by sector in Thailand.

Figure A3.14.9 CO_2 Emissions Reduction (Thailand)



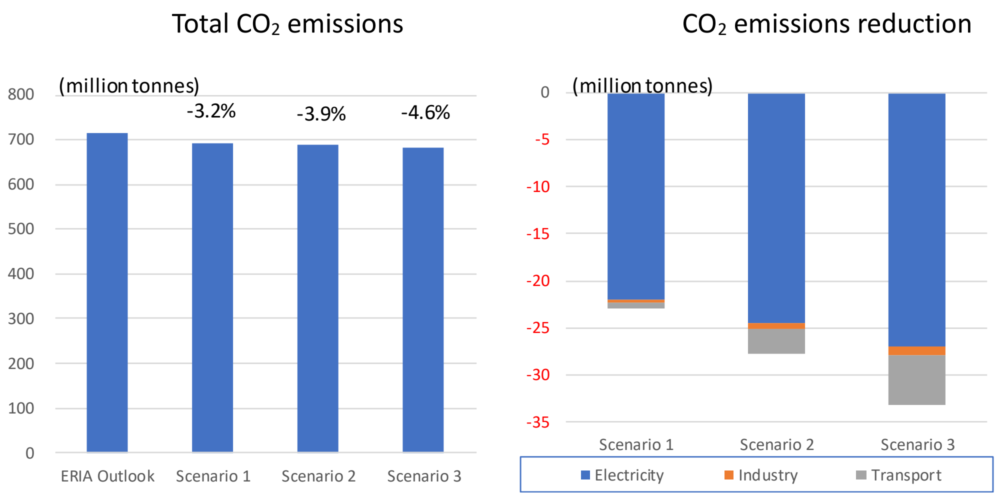
ERIA = Economic Research Institute for ASEAN and East Asia.
Source: Author.

10. Viet Nam

CO_2 emissions reduction in Viet Nam reaches 23.0 million tonnes in Scenario 1, 27.7 million tonnes in Scenario 2, and 33.2 million tonnes in Scenario 3. Viet Nam has a large CO_2 emissions reduction potential with a higher share of coal-fired electricity generation because 20% of coal-fired new electricity generation is assumed to be converted to hydrogen and natural gas mixed fuel. Viet Nam has the second-largest CO_2 reduction potential in ASEAN.

Figure A3.14.10 shows the total CO_2 emissions from fuel combustion and CO_2 emissions reduction by sector in Viet Nam.

Figure A3.14.10 CO_2 Emissions Reduction (Viet Nam)



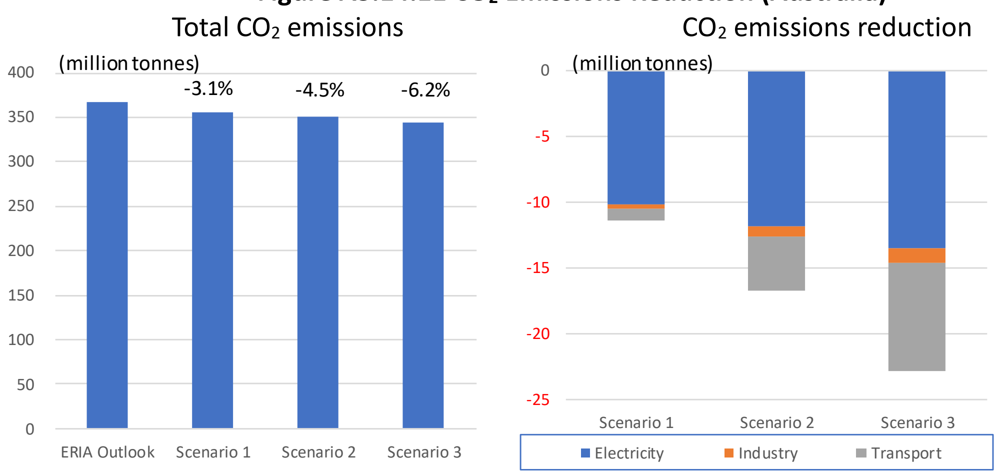
ERIA = Economic Research Institute for ASEAN and East Asia.
Source: Author.

11. Australia

CO_2 emissions reduction in Australia reaches 11.4 million tonnes in Scenario 1, 16.7 million tonnes in Scenario 2, and 22.9 million tonnes in Scenario 3.

Figure A3.14.11 shows the total CO_2 emissions from fuel combustion and CO_2 emissions reduction by sector in Australia.

Figure A3.14.11 CO_2 Emissions Reduction (Australia)



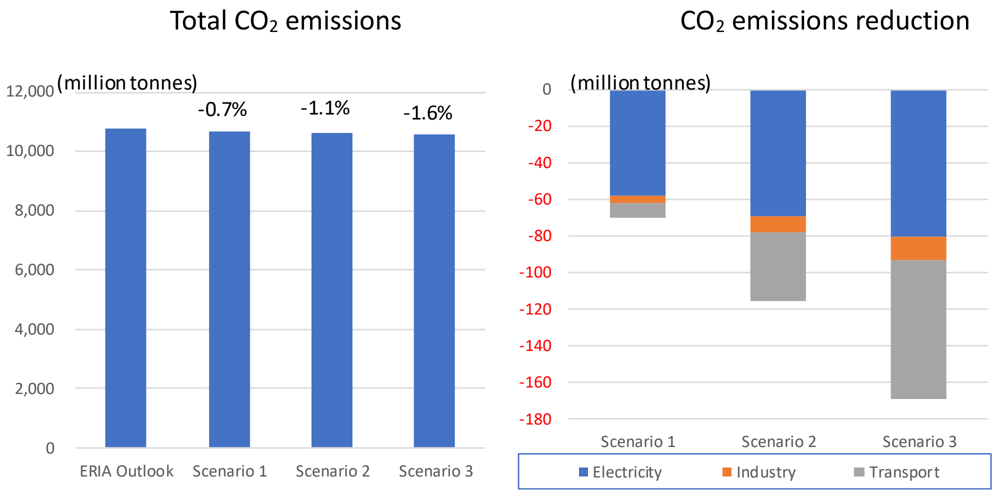
ERIA = Economic Research Institute for ASEAN and East Asia.
Source: Author.

12. China

CO_2 emissions reduction in China reaches 70.3 million tonnes in Scenario 1, 115.9 million tonnes in Scenario 2, and 169.5 million tonnes in Scenario 3. China has the second-largest CO_2 reduction potential in EAS.

Figure A3.14.12 shows the total CO_2 emissions from fuel combustion and CO_2 emissions reduction by sector in China.

Figure A3.14.12 CO_2 Emissions Reduction (China)



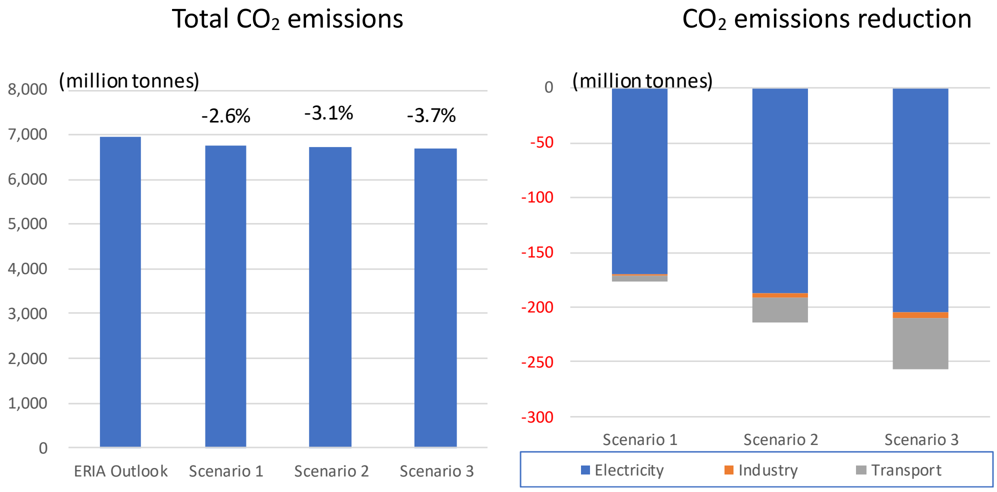
ERIA = Economic Research Institute for ASEAN and East Asia.
Source: Author.

13. India

CO_2 emissions reduction in India reaches 177.1 million tonnes in Scenario 1, 214.0 million tonnes in Scenario 2, and 256.3 million tonnes in Scenario 3. India has the largest CO_2 reduction potential with 37% share in the EAS region. The share of coal-fire electricity generation is one of the highest in the region.

Figure A3.14.13 shows the total CO_2 emissions from fuel combustion and CO_2 emissions reduction by sector in India.

Figure A3.14.13 CO_2 Emissions Reduction (India)



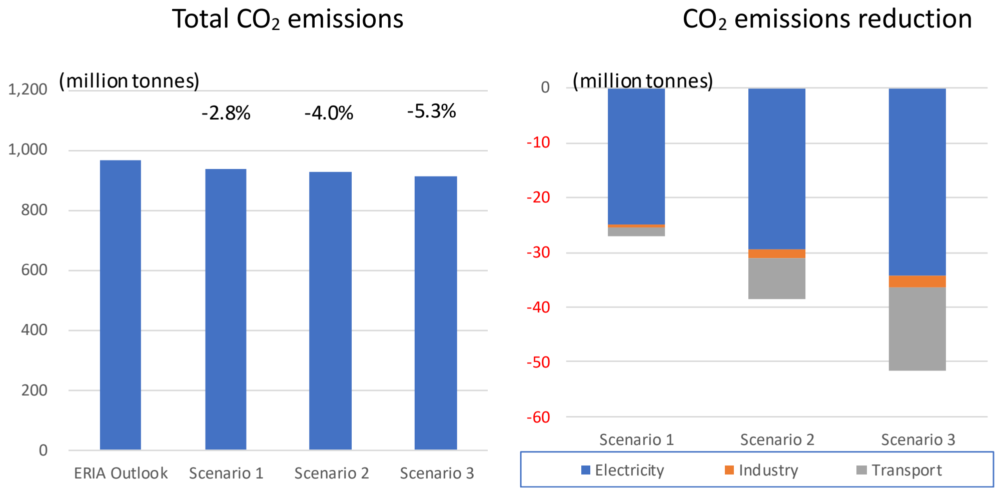
ERIA = Economic Research Institute for ASEAN and East Asia.
Source: Author.

14. Japan

CO_2 emissions reduction in Japan reaches 27.1 million tonnes in Scenario 1, 38.6 million tonnes in Scenario 2, and 51.6 million tonnes in Scenario 3.

Figure A3.14.14 shows the total CO_2 emissions from fuel combustion and CO_2 emissions reduction by sector in Japan.

Figure A3.14.14 CO_2 Emissions Reduction (Japan)



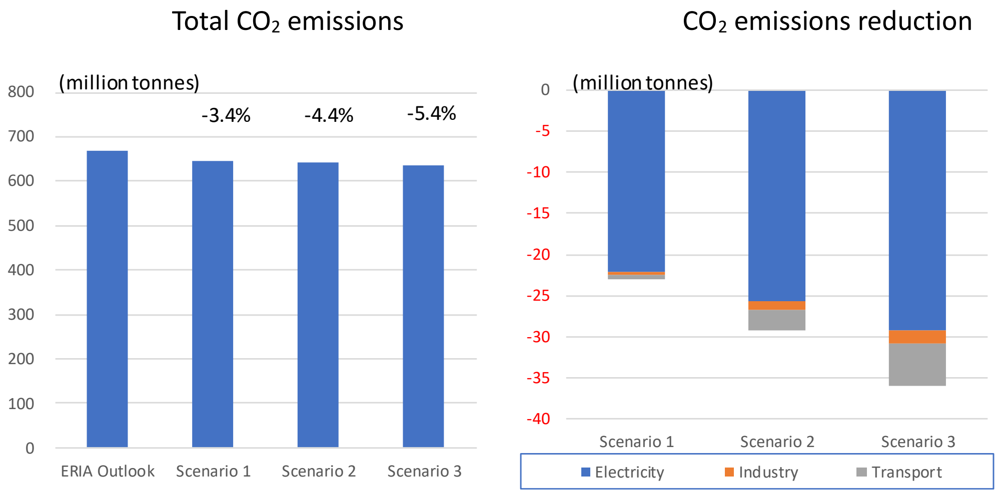
ERIA = Economic Research Institute for ASEAN and East Asia.
Source: Author.

15. Korea

CO_2 emissions reduction in Korea reaches 23.1 million tonnes in Scenario 1, 29.3 million tonnes in Scenario 2, and 36.0 million tonnes in Scenario 3.

Figure A3.14.15 shows the total CO_2 emissions from fuel combustion and CO_2 emissions reduction by sector in Korea.

Figure A3.14.15 CO_2 Emissions Reduction (Republic of Korea)



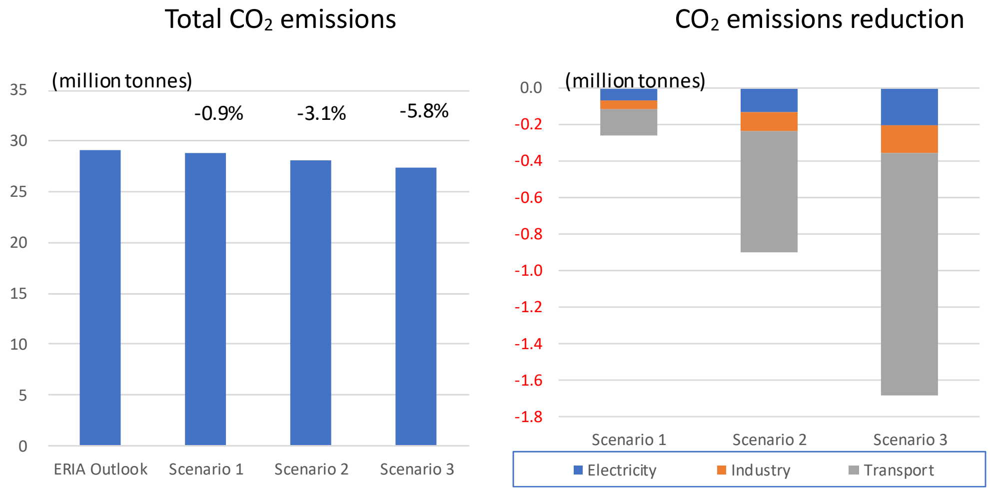
ERIA = Economic Research Institute for ASEAN and East Asia.
Source: Author.

16. New Zealand

CO_2 emissions reduction in New Zealand reaches 0.3 million tonnes in Scenario 1, 0.9 million tonnes in Scenario 2, and 1.7 million tonnes in Scenario 3.

Figure A3.14.15 shows the total CO_2 emissions from fuel combustion and CO_2 emissions reduction by sector in New Zealand.

Figure A3.14.15 CO_2 Emissions Reduction (New Zealand)



ERIA = Economic Research Institute for ASEAN and East Asia.
Source: Author.

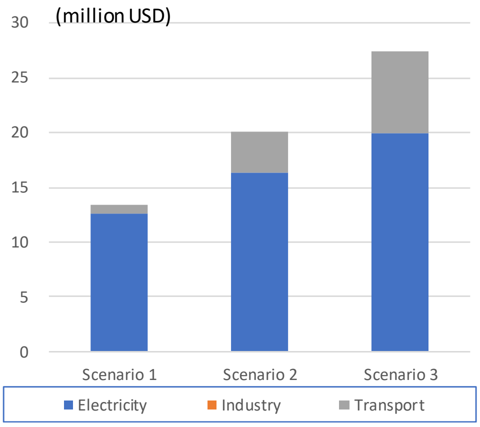
Appendix 3.15 Economic Impact of CO_2 Emissions Reduction Analysis by Country

1. Brunei Darussalam

The economic impact of CO_2 emissions reduction in Brunei Darussalam reaches $13 million in Scenario 1, $20 million in Scenario 2, and $27 million in Scenario 3.

Figure A3.15.1 shows the economic impact of CO_2 emissions reduction by sector in Brunei Darussalam.

Figure A3.15.1 Economic Impact of CO_2 Emissions Reduction (Brunei Darussalam)



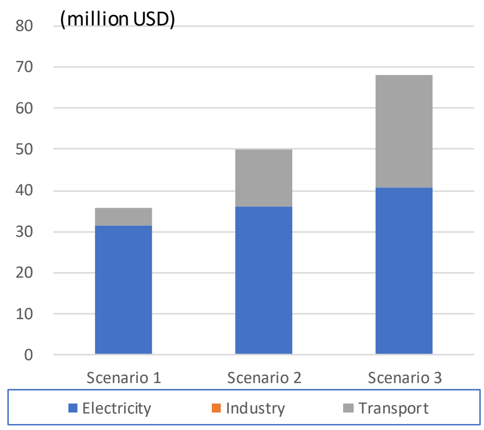
Source: Author.

2. Cambodia

The economic impact of CO_2 emissions reduction in Cambodia reaches $36 million in Scenario 1, $50 million in Scenario 2, and $68 million in Scenario 3.

Figure A3.15.2 shows the economic impact of CO_2 emissions reduction by sector in Cambodia.

Figure A3.15.2 Economic Impact of CO_2 Emissions Reduction (Cambodia)



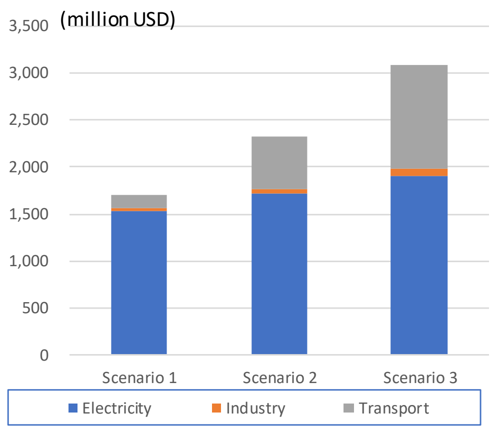
Source: Author.

3. Indonesia

The economic impact of CO_2 emissions reduction in Indonesia reaches $1.7 billion in Scenario 1, $2.3 billion in Scenario 2, and $3.1 billion in Scenario 3. Indonesia has the largest economic impact of CO_2 emissions reduction in ASEAN and the third-largest economic impact of CO_2 emissions reduction in the EAS region.

Figure A3.15.3 shows the economic impact of CO_2 emissions reduction by sector in Indonesia.

Figure A3.15.3 Economic Impact of CO_2 Emissions Reduction (Indonesia)



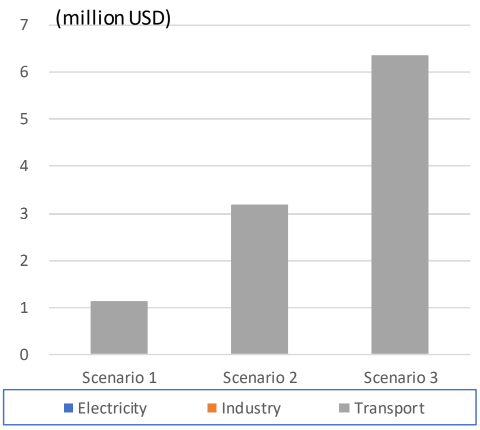
Source: Author.

4. Lao PDR

The economic impact of CO_2 emissions reduction in Lao PDR reaches $1 million in Scenario 1, $3 million in Scenario 2, and $6 million in Scenario 3.

Figure A3.15.4 shows the economic impact of CO_2 emissions reduction by sector in Lao PDR.

Figure A3.15.4 Economic Impact of CO_2 Emissions Reduction (Lao PDR)



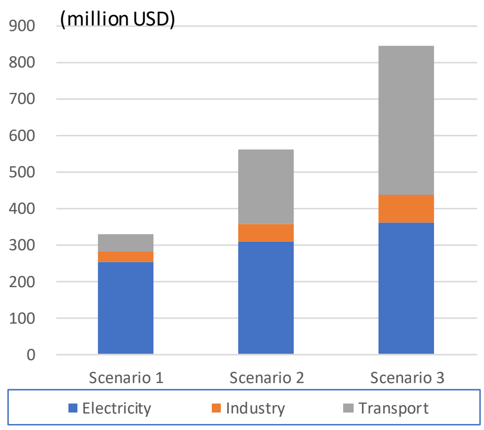
Lao PDR = Lao People's Democratic Republic.
Source: Author.

5. Malaysia

The economic impact of CO_2 emissions reduction in Malaysia reaches $329 million in Scenario 1, $563 million in Scenario 2, and $845 million in Scenario 3.

Figure A3.15.5 shows the economic impact of CO_2 emissions reduction by sector in Malaysia.

Figure A3.15.5 Economic Impact of CO_2 Emissions Reduction (Malaysia)



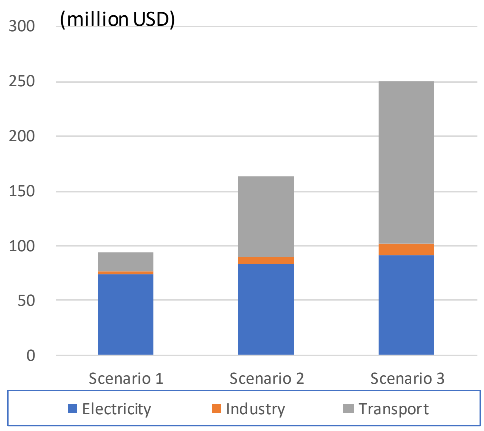
Source: Author.

6. Myanmar

The economic impact of CO_2 emissions reduction in Myanmar reaches $94 million in Scenario 1, $164 million in Scenario 2, and $250 million in Scenario 3.

Figure A3.15.6 shows the economic impact of CO_2 emissions reduction by sector in Myanmar.

Figure A3.15.6 Economic Impact of CO_2 Emissions Reduction (Myanmar)



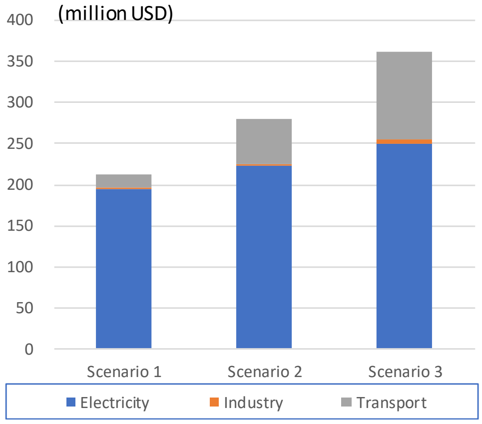
Source: Author.

7. Philippines

The economic impact of CO_2 emissions reduction in the Philippines reaches $94 million in Scenario 1, $164 million in Scenario 2, and $250 million in Scenario 3.

Figure A3.15.7 shows the economic impact of CO_2 emissions reduction by sector in the Philippines.

Figure A3.15.7 Economic Impact of CO_2 Emissions Reduction (Philippines)



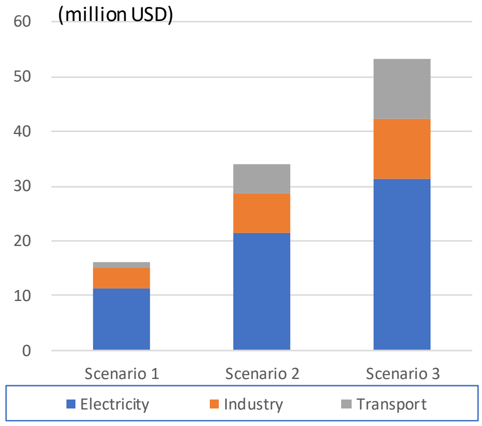
Source: Author.

8. Singapore

The economic impact of CO_2 emissions reduction in Singapore reaches $16 million in Scenario 1, $34 million in Scenario 2, and $53 million in Scenario 3.

Figure A3.15.8 shows the economic impact of CO_2 emissions reduction by sector in Singapore.

Figure A3.15.8 Economic Impact of CO_2 Emissions Reduction (Singapore)



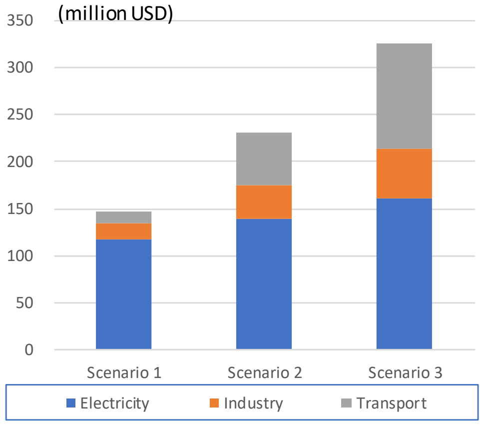
Source: Author.

9. Thailand

The economic impact of CO_2 emissions reduction in Thailand reaches $147 million in Scenario 1, $231 million in Scenario 2, and $326 million in Scenario 3.

Figure A3.15.9 shows the economic impact of CO_2 emissions reduction by sector in Thailand.

Figure A3.15.9 Economic Impact of CO_2 Emissions Reduction (Thailand)



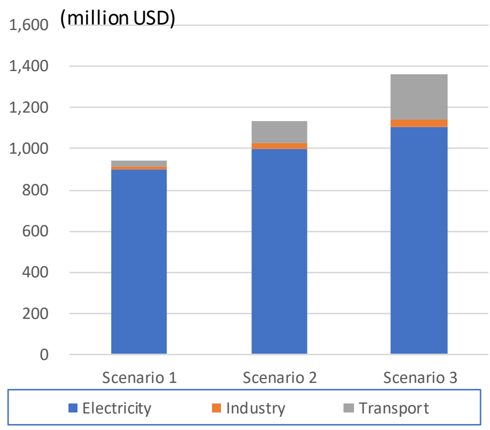
Source: Author.

10. Viet Nam

The economic impact of CO_2 emissions reduction in Viet Nam reaches $0.9 billion in Scenario 1, $1.1 billion in Scenario 2, and $1.4 billion in Scenario 3.

Figure A.15.10 shows the economic impact of CO_2 emissions reduction by sector in Viet Nam.

Figure A.15.10 Economic Impact of CO_2 Emissions Reduction (Viet Nam)



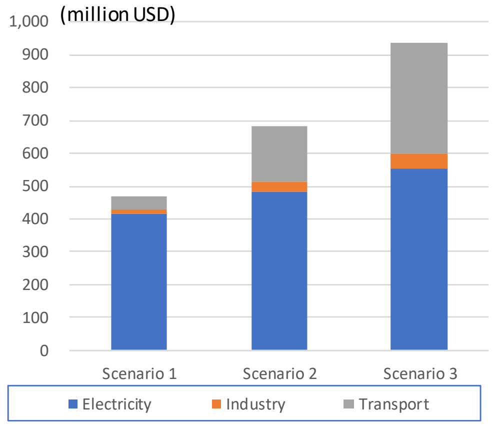
Source: Author.

11. Australia

The economic impact of CO_2 emissions reduction in Australia reaches $469 million in Scenario 1, $684 million in Scenario 2, and $938 million in Scenario 3.

Figure A3.15.11 shows the economic impact of CO_2 emissions reduction by sector in Australia.

Figure A3.15.11 Economic Impact of CO_2 Emissions Reduction (Australia)



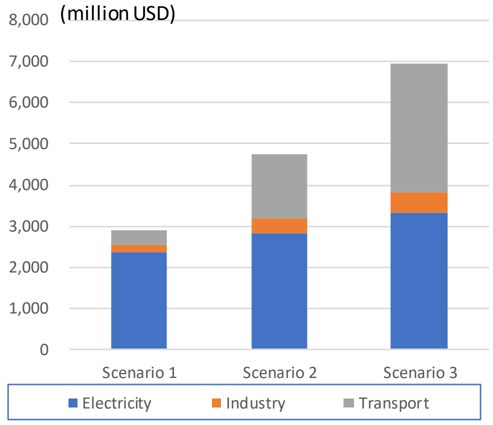
Source: Author.

12. China

The economic impact of CO_2 emissions reduction in China reaches $2.9 billion in Scenario 1, $4.8 billion in Scenario 2, and $7.0 billion in Scenario 3. China has the second-largest economic impact of CO_2 emissions reduction in EAS.

Figure A3.15.12 shows the economic impact of CO_2 emissions reduction by sector in China.

Figure A3.15.12 Economic Impact of CO_2 Emissions Reduction (China)



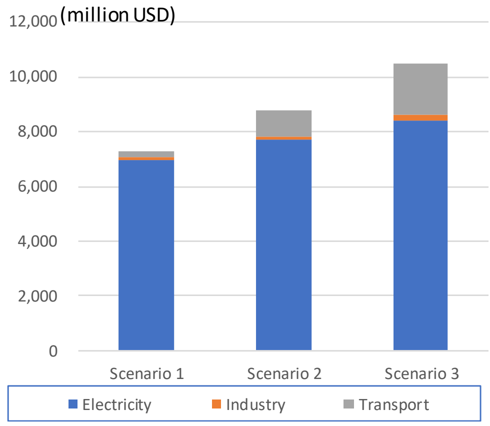
Source: Author.

13. India

The economic impact of CO_2 emissions reduction in India reaches $7.3 billion in Scenario 1, $8.8 billion in Scenario 2, and $10.5 billion in Scenario 3. India has the largest economic impact of CO_2 emissions reduction in EAS.

Figure A3.15.13 shows the economic impact of CO_2 emissions reduction by sector in India.

Figure A3.15.13 Economic Impact of CO_2 Emissions Reduction (India)



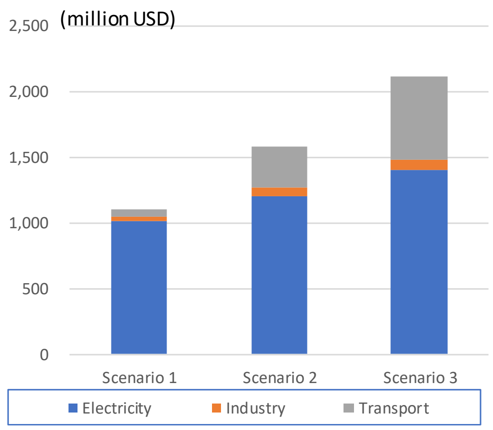
Source: Author.

14. Japan

The economic impact of CO_2 emissions reduction in Japan reaches $1.1 billion in Scenario 1, $1.6 billion in Scenario 2, and $2.1 billion in Scenario 3.

Figure A3.15.14 shows the economic impact of CO_2 emissions reduction by sector in Japan.

Figure A3.15.14 Economic Impact of CO_2 Emissions Reduction (Japan)



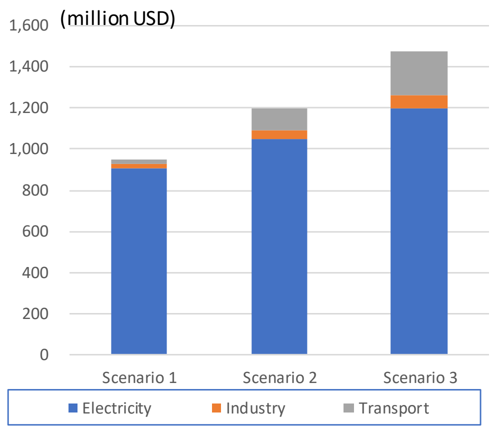
Source: Author.

15. Republic of Korea

The economic impact of CO_2 emissions reduction in Korea reaches \$0.9 billion in Scenario 1, \$1.2 billion in Scenario 2, and \$1.5 billion in Scenario 3.

Figure A3.15 15 shows the economic impact of CO_2 emissions reduction by sector in Korea.

Figure A3.15 15 Economic Impact of CO_2 Emissions Reduction (Republic of Korea)



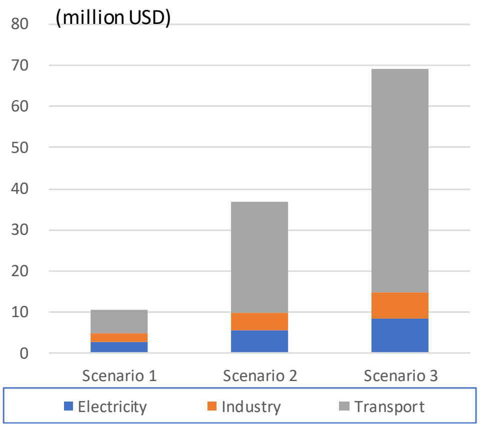
Source: Author.

16. New Zealand

The economic impact of CO_2 emissions reduction in New Zealand reaches $11 million in Scenario 1, $37 million in Scenario 2, and $69 million in Scenario 3.

Figure A3.15.16 shows the economic impact of CO_2 emissions reduction by sector in New Zealand.

Figure A3.15.16 Economic Impact of CO_2 Emissions Reduction (New Zealand)



Source: Author.

Chapter 4
The Potential and Costs of Hydrogen Supply

1. Hydrogen Production Potential

1.1 Hydrogen Production Method

Hydrogen can be produced from any kind of primary energy, from fossil fuel to renewables; major hydrogen sources are shown in Figure 4.1.

Three major fossil fuel production methods are listed: (1) by-product hydrogen utilising purification technologies, such as Pressure Swing Adsorption; (2) reformed hydrogen from gas flares, reinjection, and mid-small gas fields; and (3) gasified liquid (vacuum residue, pitch) and solid (coke, coal, lignite) hydrogen utilising gasification technology.

In addition, it is important to effectively manage the CO_2 that will be produced during hydrogen production. CO_2 can be captured and utilised for enhanced oil recovery or feedstock for chemical products or stored underground.

Renewable electricity, such as from solar, wind, hydro, and geothermal sources can be converted to hydrogen through water electrolysis, and biomass can also produce hydrogen via gasification.

In the future, new technology, such as biotechnology and photo-catalysts, will diversify and increase the options to produce hydrogen from renewables.

Figure 4.1 Hydrogen Production Methods

HYDROGEN from Fossil Fuel

- **By-product hydrogen** (CCR, ethylene, methanol, chlor-alkali)
- **Reformed hydrogen** (flare gas, reinjection gas, mid-small gas field)
- **Gasified hydrogen** (VR/ pitch / coke, coal / lignite)

+

- **CCUS** (CO2-EOR, CCS, CO2 feedstock)

HYDROGEN from Renewable Energy

- **Water electrolysis hydrogen** (solar, wind, hydro, geothermal)
- **Biomass hydrogen** (waste, unutilized, resource crop)

< Technology Development >

- **Biotech hydrogen** (microalgae, bacterium, etc.)
- **Photo-catalyst hydrogen** (Solar)

CCR = Conradson carbon residue, CCS = carbon capture and storage, CCUS = carbon capture, utilisation and storage, EOR = enhanced oil recovery, VR = vacuum residue.
Source: Author.

1.2. Hydrogen Production Cost

1.2.1. Key Assumptions

Key assumptions are made to calculate the costs of each hydrogen production method (technology and source), as shown in Table 4.1.

Table 4.1 Key Assumptions of Each Hydrogen Production Method

TECHNOLOGY	H2 SOURCE	Key Assumptions	Data Source
Reforming	Gas (Flare, Mid – small)	• Investment cost ($2,000/Nm3/h@2017, $1,650/Nm3/h@2040) • Efficiency (64%@2017, 83%@2040)	IEA report
Gasification	Lignite	• Investment cost ($10,000/Nm3/h@2017, $8,890/Nm3/h@2040) • Efficiency (42%@2017, 53 %@2040)	AIST report
CCUS	-	• CCS cost ($70/tonne@2015, $48/tonne@2040) • CO2 value ($20/ton@Best)	NCCS report
Gasification	Biomass	• Investment cost ($5,222/Nm3/h@2017, $4,700/Nm3/h@2040) • Efficiency (44%@2017, 50%@2040)	In-house data
Electrolysis	Solar, Wind, Hydro, Geothermal	• Investment cost ($5,936/Nm3/h@2017, $2,947/Nm3/h@2040) • Efficiency (79%@2017, 82%@2040)	IEA report IEEJ report

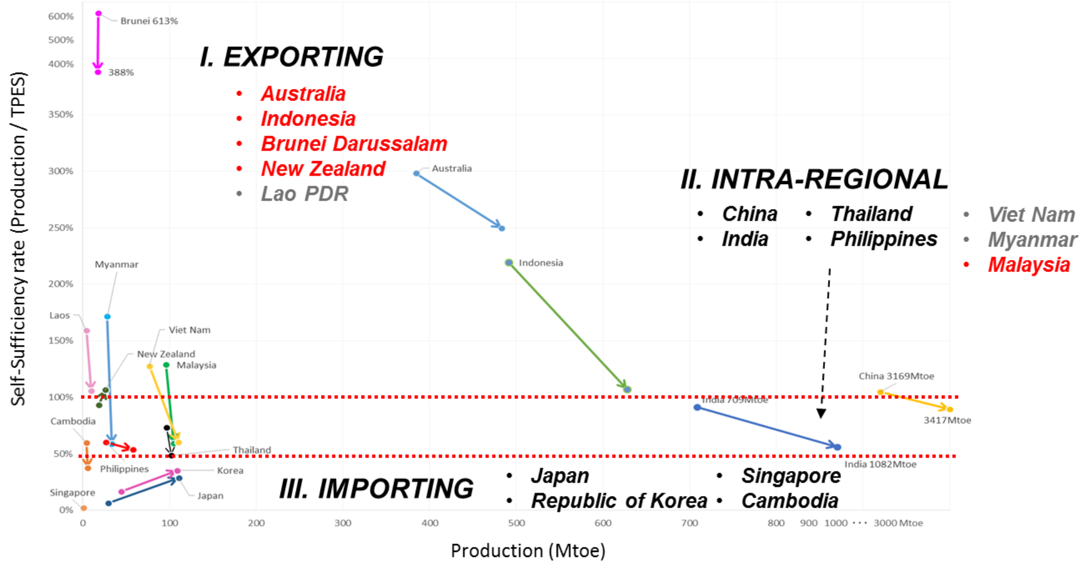
AIST = Association for Iron and Steel Technology, CCUS = carbon capture storage, IEA = International Energy Association, IEEJ = Institute of Electrical Engineers of Japan, NCCS = National Climate Change Secretariat.
Source: Author.

Using forecasted data of the energy balance between production and demand, including the hydrogen forecast, the 16 East Asia Summit (EAS) countries are categorised into three groups (Exporting, Intra-regional, Importing) to identify their positioning for hydrogen trading in 2040, as shown in Figure 4.2.

Addressing regional energy balance characteristics, Malaysia and Indonesia are divided into two regions each: In Malaysia 'Peninsular Malaysia' is the more demand-intensive region and 'Borneo' is the more supply-intensive region, while in Indonesia 'Eastern regions (Kalimantan, Natuna, Maluku, Papua, and Sulawesi)' is the more demand-intensive region and 'Java and Sumatra' is a demand-and-supply balanced region.

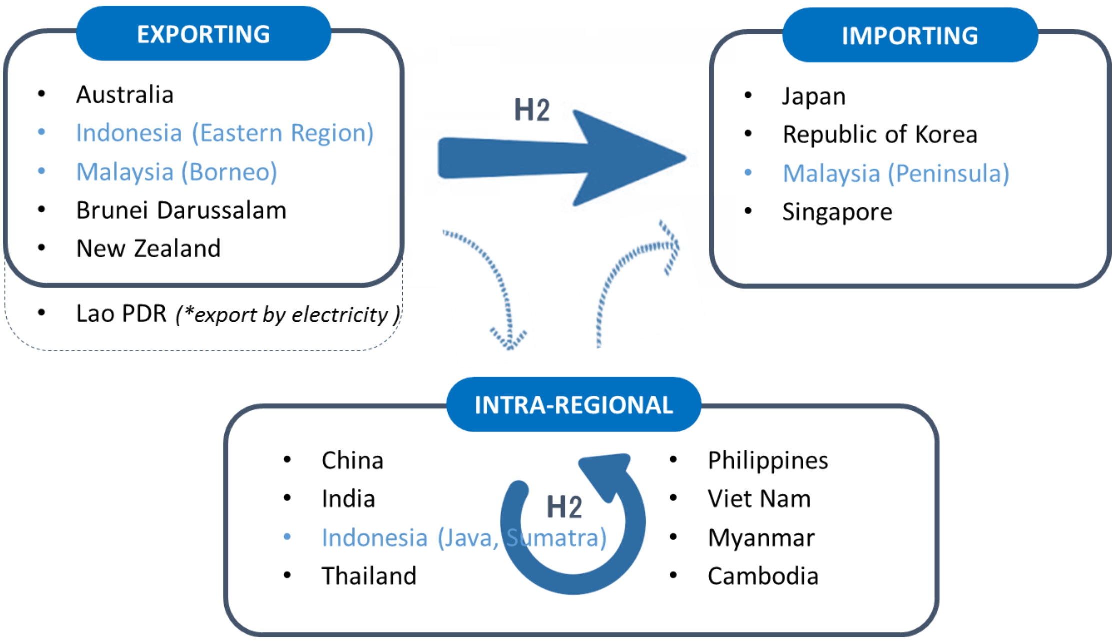
As the result, the supply-intensive 5 + 1 countries/regions will potentially be in a hydrogen 'Exporting' position, while the other four will be in the hydrogen 'Importing' group, and the remaining eight will be in the 'Intra-regional' group, as shown in Figure 4.3.

Figure 4.2 Self-Sufficiency Rate in Total Primary Energy Supply (2013–2040)



Mtoe = million tonnes of oil equivalent, TPES = total primary energy supply.
Source: Author; the data were customised based on Kimura and Phoumin, 2016.

Figure 4.3 Positioning for Hydrogen Trading



Source: Author.

1.2.2. Hydrogen Production Cost

Figure 4.4 compares the typical costs of hydrogen produced from fossil fuels and renewable energy in the Exporting group, with the same comparison presented for the Intra-regional group in Figure 4.5. The hydrogen costs are calculated based on public information from References [1].

The costs of each production technology are estimated in three scenarios, namely the Current scenario, the 2040 scenario, and the Best (New Tech or Future Tech) scenario. For the Exporting group, hydrogen production costs in 2040 ranked from low to high are in the order of 'Gas reforming', 'Water electrolysis (with stable power)', 'Biomass gasification', 'Lignite gasification', and 'Water electrolysis (with fluctuating power)'.

Hydrogen production will strongly depend on the price of feedstocks and process efficiency. The feedstock prices of each hydrogen production pathway for the three scenarios are presented in Table 4.2 for the Exporting group and Table 4.3 for the Intra-regional group.

Table 4.2 Feedstock Prices Applied to Evaluate Hydrogen Cost for Each Pathway (Exporting Group)

Hydrogen production pathway	Feedstock	Unit	Current	2040	Best
Steam reforming w/CCS	NG	US$/mmbtu	3.4	5.7	5.7
Alkaline electrolyser/stable power	Electricity	C/kWh	5.2	3.1	3.1
Lignite gasification w/CCS	Lignite	US$/tonne	39.8	55.7	55.7
Woody biomass gasification	Wood	US$/tonne	100	100	100
Alkaline electrolyser/fluctuating power	Electricity	C/kWh	8.0	2.5	N/A

CCS = carbon capture and storage, NG = natural gas.
Source: Author.

[1] Environmental Energy Team (2014); Forestry and Forest Products Research Institute (2017); Fujimoto (2018); Ishii and Maruta (2018); Karimi and Shamsuzzaman (2014); Kato (2016); Korner (2015); Sayama and Miseki (2014); and Yamamoto (2018).

Table 4.3 Feedstock Prices Applied to Evaluate Hydrogen Cost for Each Pathway (Intra-regional Group)

Hydrogen Production Pathway	Feedstock	Unit	Current	2040	Best
Steam reforming w/CCS	NG	US$/mmbtu	5.9	9.9	9.9
Alkaline electrolyser/stable power	Electricity	C/kWh	5.2	3.1	3.1
Lignite gasification w/CCS	Lignite	US$/tonne	32.2	45.1	45.1
Woody biomass gasification	Wood	US$/tonne	100	100	100
Alkaline electrolyser/fluctuating power	Electricity	C/kWh	8.0	2.5	N/A

CCS = carbon capture and storage, NG = natural gas.
Source: Author.

In the case of production from fossil fuel sources, it is also required to assess the feasibility of carbon capture utilisation and storage (CCUS), reflecting the considerations on social acceptability, technology and economics.

CCUS consists of CCS and carbon capture and utilisation (CCU). CCS is cost-based activity and it is required to add its cost (CCS cost) to hydrogen production. CCU is value-based activity and it is required to deduct its value (CO_2 value) from hydrogen production.

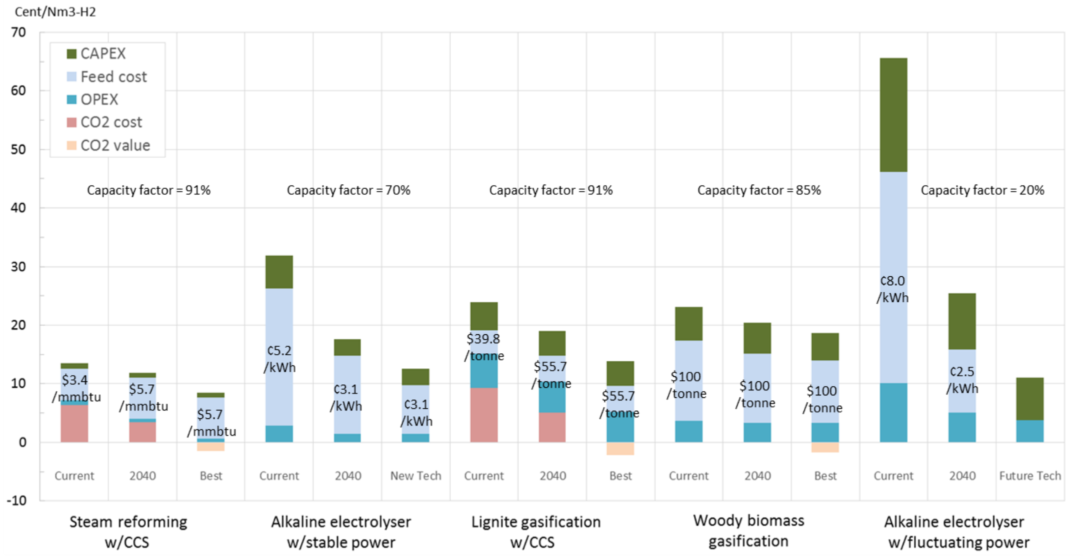
The capacity factor, CCS cost and CO_2 value used in the calculation of hydrogen production costs are shown in Table 4.4.

Table 4.4 Assumptions for Capacity Factor, CCS Cost and CO_2 Value

Hydrogen production pathway	Capacity factor (%)	CCS cost Current (US$/t-$CO_2$)	CCS cost 2040 (US$/t-$CO_2$)	CO_2 value Best case (US$/t-$CO_2$)
Steam reforming w/CCS	91.3	70.0	48.0	20.0
Alkaline electrolyser/stable power	70.0	NA	NA	NA
Lignite gasification w/CCS	91.3	70.0	48.0	20.0
Woody biomass gasification	85.0	NA	NA	20.0
Alkaline electrolyser/fluctuating power	20.0	NA	NA	NA

CCS = carbon capture and storage.
Source: Author.

Figure 4.4 Example of Large-Scale Hydrogen Production Cost (Exporting Group)

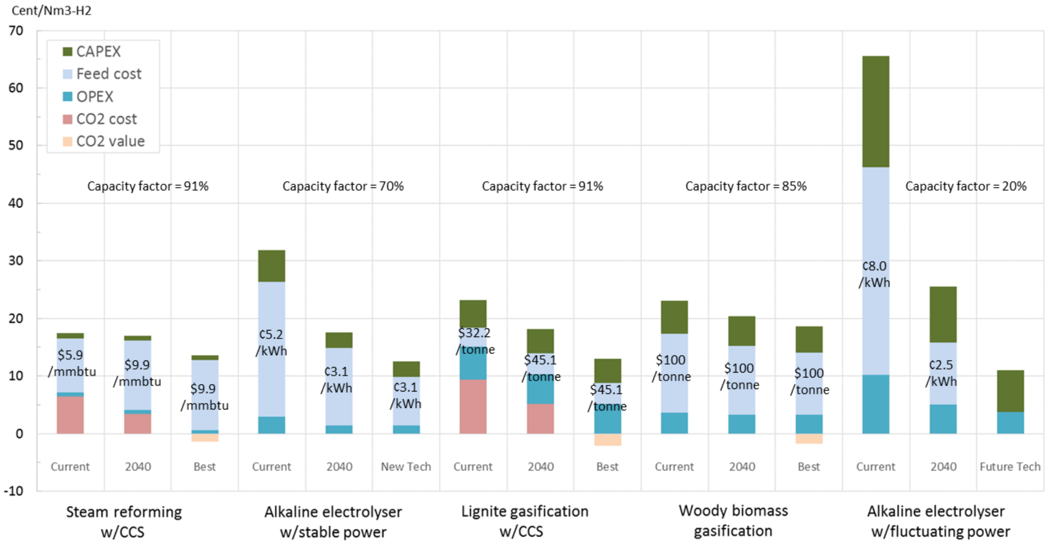


*1 : Feed Cost of Lignite gasification is based on FOB price in Exporting Group Countries.
*2 : CCS cost is based on $70/t-CO2 for current and $48/t-CO2 for 2040 (CCS/Utilization Singapore Perspectives).

CAPEX = capital expenditure, CCS = carbon capture and storage, FOB = free on board, OPEX = operating expenditure.
Source: Author.

Figure 4.5 shows the cost comparison of hydrogen produced from fossil fuels and renewable energy in the countries of Intra-regional Group. General trend of cost is same as the one in Exporting Group, and only costs of steam reforming and lignite gasification are different due to the difference of feedstock price between two groups.

Figure 4.5 Example of Large-Scale Hydrogen Production Cost (Intra-regional Group)



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

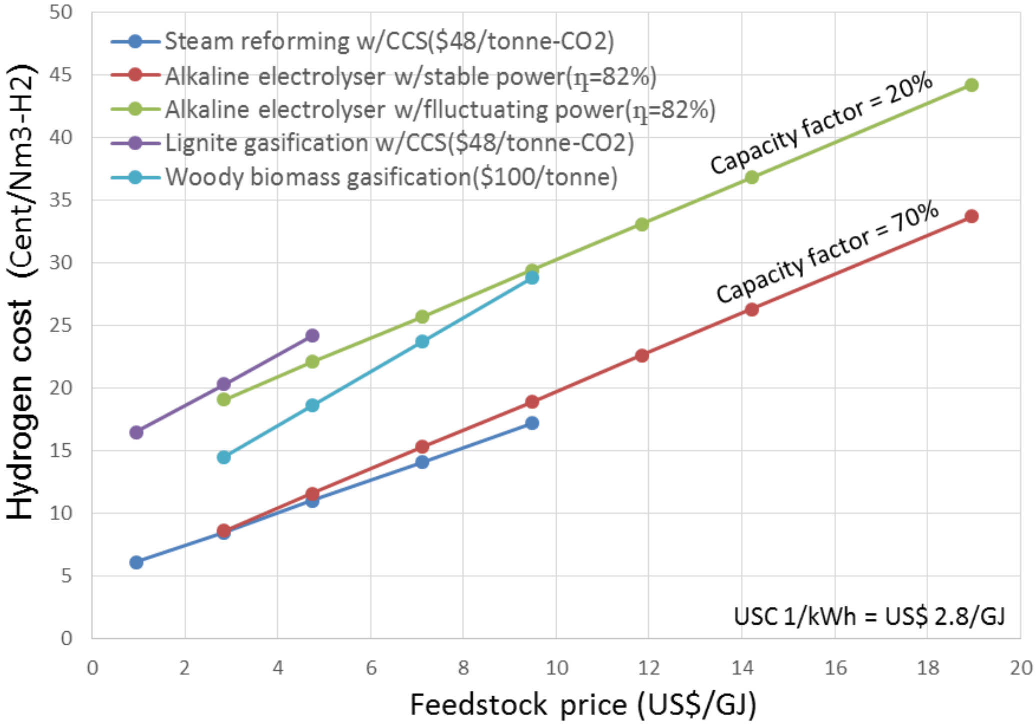
CAPEX = capital expenditure, CCS = carbon capture and storage, FOT = free on truck, OPEX = operating expenditure.
Source: Author.

1.2.3. Sensitivity Analysis

The sensitivity of hydrogen production costs to feedstock price changes is illustrated in Figure 4.6, which compares different hydrogen production costs using normalised feedstock prices as a variable parameter.

Hydrogen production cost by gas reforming is the most economical method. Water electrolysis with a high capacity factor (70%) plus a low feedstock price will enhance its cost competitiveness. Lignite gasification with CCS (US$48/tonne-$CO_2$) and woody biomass gasification shows same level of hydrogen production cost, and water electrolysis with low capacity factor shows the highest range of its cost.

Figure 4.6 Sensitivity of Hydrogen Production Cost (2040) by Feedstock Price

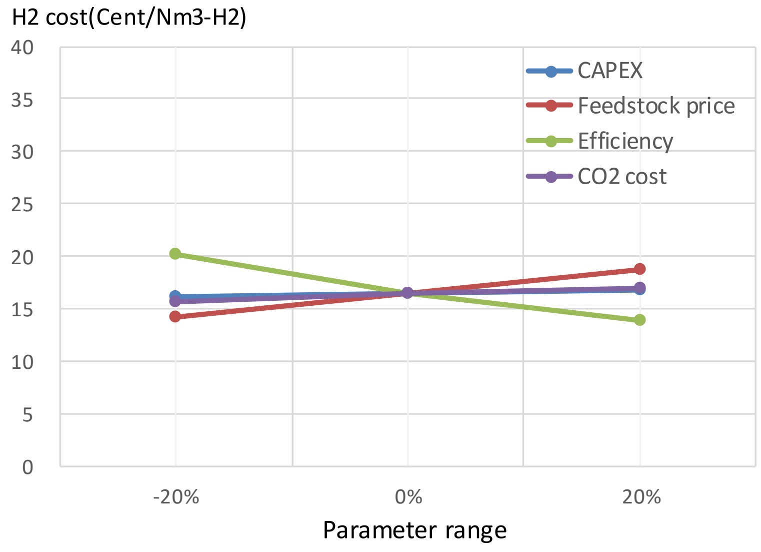


CCS = carbon capture and storage.
Source: Author.

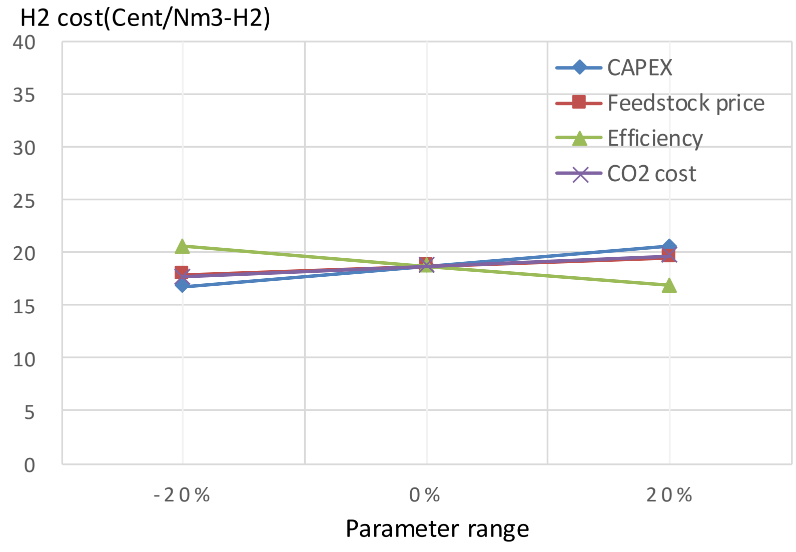
The sensitivity of parameters of ‘CAPEX’, ‘Feedstock price’, ‘Efficiency’, and ‘CO_2 Cost’ on the cost of each hydrogen production technology is illustrated in Figure 4.7. The parameters are varied by 20% higher and lower, relative to the base design condition. The conditions of technology development are assumed in the operation year of the production plants around 2040.

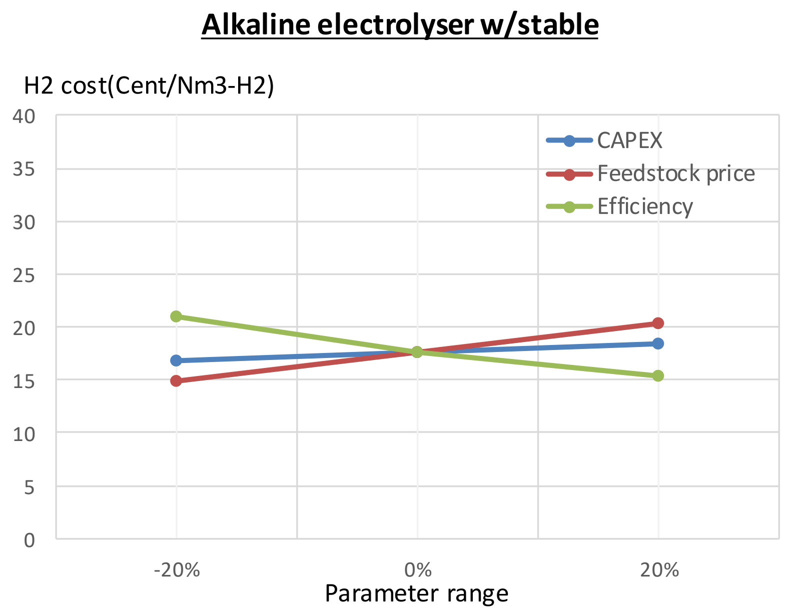
Figure 4.7 Sensitivity of Hydrogen Production Cost to Technical Parameters (2040)

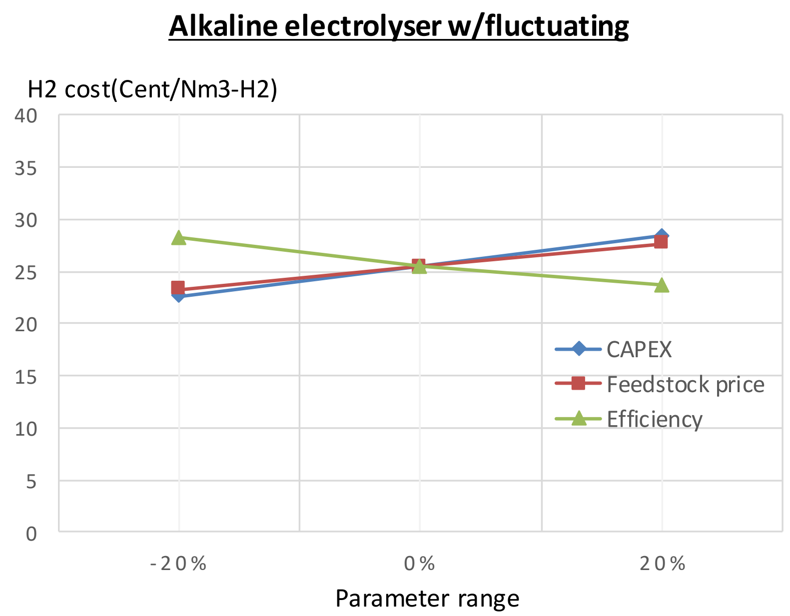
Gas Reforming



Lignite







CAPEX = capital expenditure.
Source: Author.

As for gas reforming, a +/- 20% change in feedstock price will lead to a variation of 4.6 Cent/Nm3-H_2; with lignite gasification, the same change will lead to a variation of 1.6 Cent/Nm3-H_2. On the other hand, a +/- 20% change in capital expenditure (CAPEX) will lead to a variation of 0.6 Cent/Nm3-H_2 for gas reforming and 3.8 Cent/Nm3-H_2 for lignite gasification. This means that the CAPEX of lignite gasification has a dominant effect on the hydrogen production cost compared to gas reforming. In the case of renewable energy, a +/-20% change in electricity price of stable power will lead to a variation of 5.4 Cent/Nm-H_2, while the case of fluctuating power, the variation is 4.4 Cent/Nm3-H_2. On the other hand, a +/- 20% change in CAPEX will lead to a variation of 1.6 Cent/Nm3-H_2 for stable power and 5.8 Cent/Nm3-H_2 for fluctuating power. This means that electricity price has a dominant effect on hydrogen production costs from renewable energy, and CAPEX of water electrolysers with fluctuating power will also largely affect hydrogen production cost.

The efficiency parameter has a reverse effect on the hydrogen production cost compared to the feedstock price, because an increase in efficiency causes a decrease in feedstock volume, which has a same effect on the production cost as the feedstock price.

1.3. Potential of Hydrogen Production Volume

1.3.1. Method of Estimation/Calculation

Hydrogen production volume is estimated for its potential together with a forecast as defined in Figure 4.8. Hydrogen production potential shows the technically feasible volume once geographical location, environmental conditions/constraints, etc. are considered. On the other hand, the hydrogen forecast shows the required hydrogen volume balanced with its expected demand in 2040, estimated as the total primary energy supply (TPES = demand x 1.5) of hydrogen. The ratio 1.5 is referred to the ratio between TPES and energy demand in Japan (Agency for Natural Resources and Energy, 2017).

Figure 4.8 Definitions of Hydrogen Production Potential and Forecast

Production Potential

Technically Feasible H2 Production Volume Potential in 2040

- Feasible land/area (excluding natural reserved, pasture, cropland and residential areas, etc.)
- Vicinity of coastal lines/ports in Exporting countries
- Feasible distance from populated area for inland transport in Intra-regional/Importing countries
- Balance between CO2 emissions from H2 production by fossil fuels and CO2 storage/usage potentials.
- Strong solar/wind (Solar : > 5kWh/m2, Wind : > 6m/s)

Production Forecast

H2 volume forecast to produce balanced with its TPES (demand x1.5) in 2040

- Exporting countries ('potentials' x 'introduction factor [as below]')
  by-product, gas reforming : 61%, stable RE : 29%
  biomass/lignite gasification : 5%, unstable RE : 1% below
- Intra-regional countries
  total production is 150% of total demand (Priority is lower cost H2.)
- Importing countries
  total production is all the potential H2 production.

RE = renewable energy, TPES = total primary energy supply.
Source: Author.

Hydrogen production potential volume is calculated based on the preconditions shown in Table 4.5 for fossil fuels, and Table 4.6 for renewables.

Hydrogen from fossil fuels is calculated based on the material balance of the related processes, excluding the hydrogen consumed in the plant, and some portion of gas and lignite reserves (see Table 4.5).

Table 4.5 Preconditions to Calculate Production Potential (Fossil Fuel)

TYPE	H2 SOURCE	LOGIC	Data Source
By-product (Purification)	CCR, Ethylene, Propylene, Methanol, chlor-alkali electrolysis	• Calculate based on petro/chemical production capacity and process balance for existing/planned plants, excluding internal consumption • Calculate H2 export potential by using 10% of the potential.	Interview and site visit in Thailand and India
Gas (Reforming)	Flare gas, Mid - small gas field	• Calculate based on the process balance for flare gas, mid small-gas field, using typical gas composition. • 100% of flare gas and 21.4% of gas reserve(mid-small gas) for potential	NOAA IHS Energy UN Energy Statistic Year book 2015, BP Statistics, government statistics
Liquid/Solid (Gasification)	VR/pitch, Coke, Coal/Lignite	• Calculate based on the process balance, using typical VR and Lignite composition and production volume - VR/Coke: heavy oil percentage in the refinery production capacity - Lignite: 50% of lignite reserves	Heavy oil import rate from middle east (government statistics, ERIA, APEC data) 'Petro & Petro-chemical industry in Asia 2017', 'Petro-chemical industry in Asia 2018'
CCUS	CO2-EOR, CCS, CO2 feedstock	• Calculate expected reserve period based on the CO2 volume by H2 production from fossil fuel and CCS reserve potential.	GCCSI

APEC = Asia–Pacific Economic Cooperation, CCR = Conradson carbon residue, CCS = carbon capture and storage, EOR = enhanced oil recovery, ERIA = Economic Research Institute for ASEAN and East Asia, GCCSI = Global CSS Institute, IHS = IHS Markit, NOAA = National Oceanic and Atmospheric Administration, VR = vacuum residue.
Source: Author.

Hydrogen from renewable energy is calculated based on energy intensity, geographical conditions, and technical feasibility, including some economical perspectives, e.g. distance from the coastal lines, for each source, by using public information (see Table 4.6).

Table 4.6 Preconditions to Calculate Production Potential (Renewable Energy)

TYPE	H2 SOURCE	LOGIC	Data Source
Light Energy (Electrolysis)	Solar (PV, Solar thermal)	• Calculate based on the energy intensity, geographical conditions, technical and economical feasibility.	BNERI, CIEMAT, IRENA, Kaung Kyaw Say, Mot MacDonald, NREL, RED, SEDA, government statistics
Kinetic Energy (Electrolysis)	Wind	• Same as above	AWS, BNERI, Contact Energy, INWEA, IRENA, MOIT, Vortex
Kinetic Energy (Electrolysis)	Hydro	• Employ public data for technical, commercial feasible potential of hydro power in its rich resource and island countries (AUS, NZ, Indonesia, Malaysia-Borneo)	BNERI, Contact Energy, ERIA
Heat Energy (Electrolysis)	Geothermal	• Same as above (NZ, Indonesia)	Contact Energy, IEA, IRENA, government statistics
Biomass Energy (Gasification)	Waste, unutilised, Resource crop	• Calculate H2 production potential by using 60% of total biomass potential from public data (Remaining 40% is for biofuel)	BNERI, IEA, IRENA, NOAA (*sourced by IRENA [9])

AWS = AWS Truepower, BNERI = Brunei National Energy Research Institute, CIEMAT = Research Centre for Energy, Environment and Technology, ERIA = Economic Research Institute for ASEAN and East Asia, IEA = International Energy Agency, INWEA = Indian Wind Energy Association, IRENA = International Renewable Energy Agency, MOIT = Ministry of Industry and Trade, NOAA = National Oceanic and Atmospheric Administration, NREL = National Renewable Energy Laboratory, PV = photovoltaics, RED = Renewable Energy Development Programme, SEDA = Sustainable Energy Development Authority.
Source: Author.

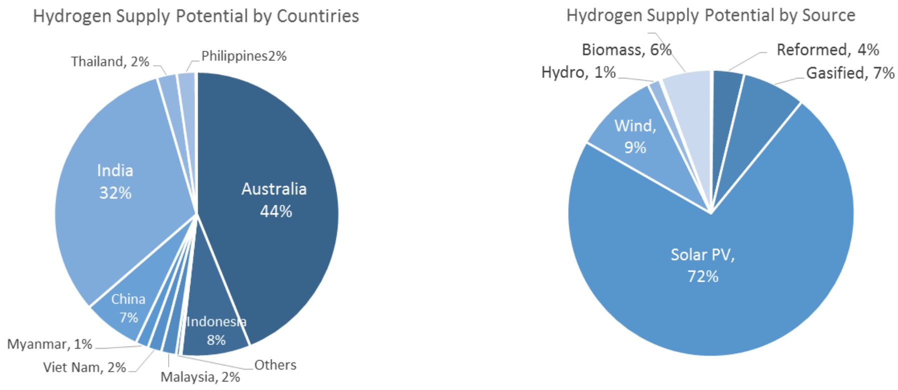
1.3.2. Hydrogen Production Potential

The total hydrogen supply potential across the EAS region is 1,876 Mtoe, with Australia accounting for 44%, followed by India with 32%, as shown in Figure 4.9.

Overall, renewable energy-derived hydrogen is assumed to account for almost 90% of the total of region’s supply potential, with hydrogen from solar photovoltaics accounting for over 70%, followed by hydrogen from wind.

Amongst fossil fuel-derived hydrogen, supplies from gasification, mostly stemming from lignite, will account for 65% of the total, followed by reformed hydrogen with 33%, derived from flare gas, reinjection gas, and mid-small gas fields.

Figure 4.9 Hydrogen Supply Potential by Countries and Source



PV = photovoltaics.

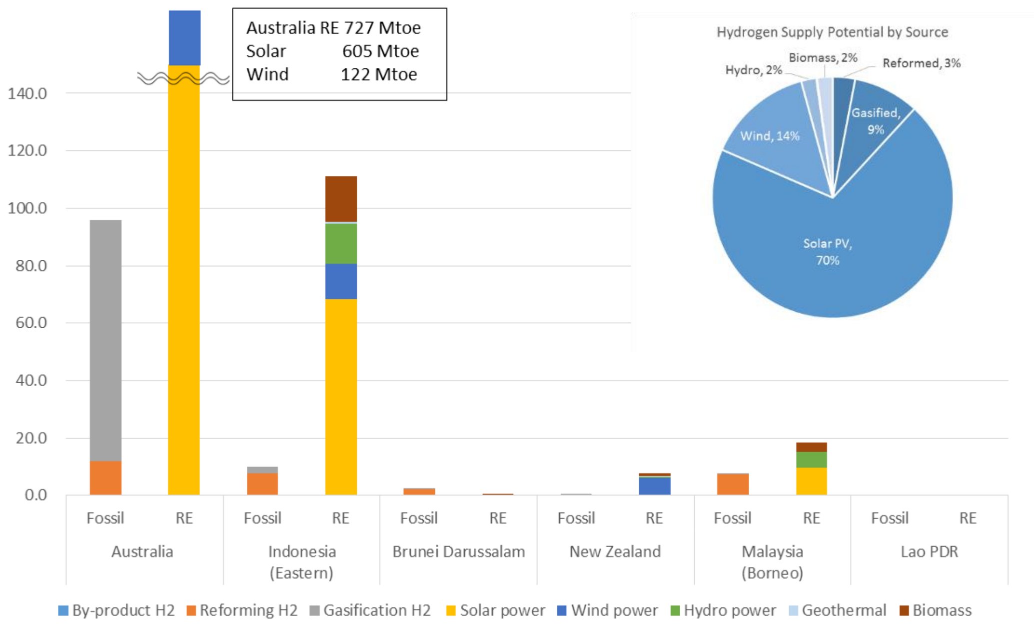
Source: Author.

The hydrogen supply potential in Exporting group countries can reach 982 Mtoe, with Australia accounting for 84%, followed by the Eastern regions of Indonesia, and then the Borneo region of Malaysia, as shown in Figure 4.10.

Renewable energy-derived hydrogen accounts for 88% of the group's supply potential, with photovoltaics (79%) taking the largest share, followed by hydrogen from wind with 16%. Fossil fuel-derived hydrogen mostly comes from lignite gasification, accounting for 74% of the total, followed by 25% of gas-reformed hydrogen.

As the largest supplier of hydrogen in the group, Australia has a potential of 823 Mtoe, mostly derived from photovoltaics, accounting for 74%, followed by wind with 15%. As the second-largest supplier, the Eastern regions of Indonesia has a potential of 121Mtoe, with photovoltaics taking the largest share at 57%, followed by biomass gasification at 13%, and then hydro and wind power. The Borneo region of Malaysia is the third-largest supplier at 26 Mtoe of hydrogen, with photovoltaics accounting for 37%, followed by gas-reformed hydrogen with 28%, then hydro with 21%.

Figure 4.10 Hydrogen Production Potential in 2040 (Exporting Group)



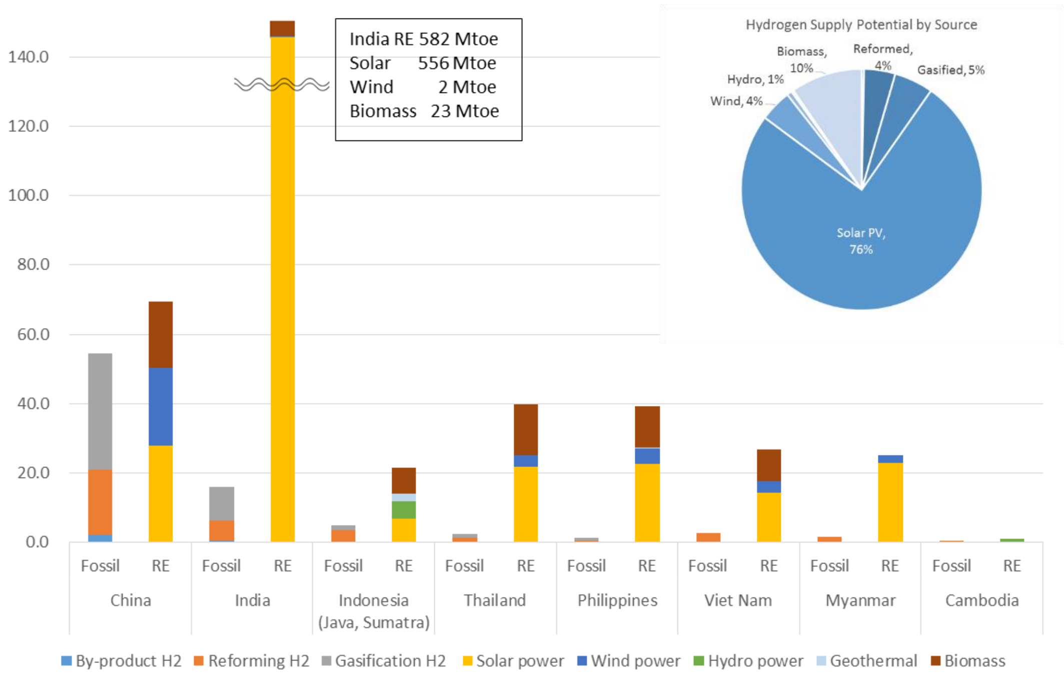
Lao PDR = Lao People's Democratic Republic, mtoe = million tonnes of oil equivalent, PV = photovoltaics, RE = renewable energy.
Source: Author.

Amongst Intra-regional group countries, the total of hydrogen supply potential can reach 890 Mtoe, with India accounting for 67%, followed by China at 14%, as shown in Figure 4.11.

Renewable energy-derived hydrogen accounts for 90% of the group's supply potential, with hydrogen from photovoltaics taking the largest share at 84%, followed by biomass gasification at 11%. Amongst fossil fuel-derived hydrogen, reformed gas accounts for 41%, followed by lignite gasification with 39%.

As the largest supplier of hydrogen in the group, India has the potential for 598 Mtoe, mostly derived from photovoltaics, accounting for 93%, followed by biomass. As the second-largest supplier, China has a potential of 124 Mtoe, mostly from photovoltaics (23%), followed by lignite gasification (19%) and then wind and biomass gasification. Thailand and the Philippines maintain the third position, showing a similar hydrogen portfolio, with photovoltaics accounting for almost the half of the potential, followed by biomass, then wind power.

Figure 4.11 Hydrogen Production Potential in 2040 (Intra-regional Group)

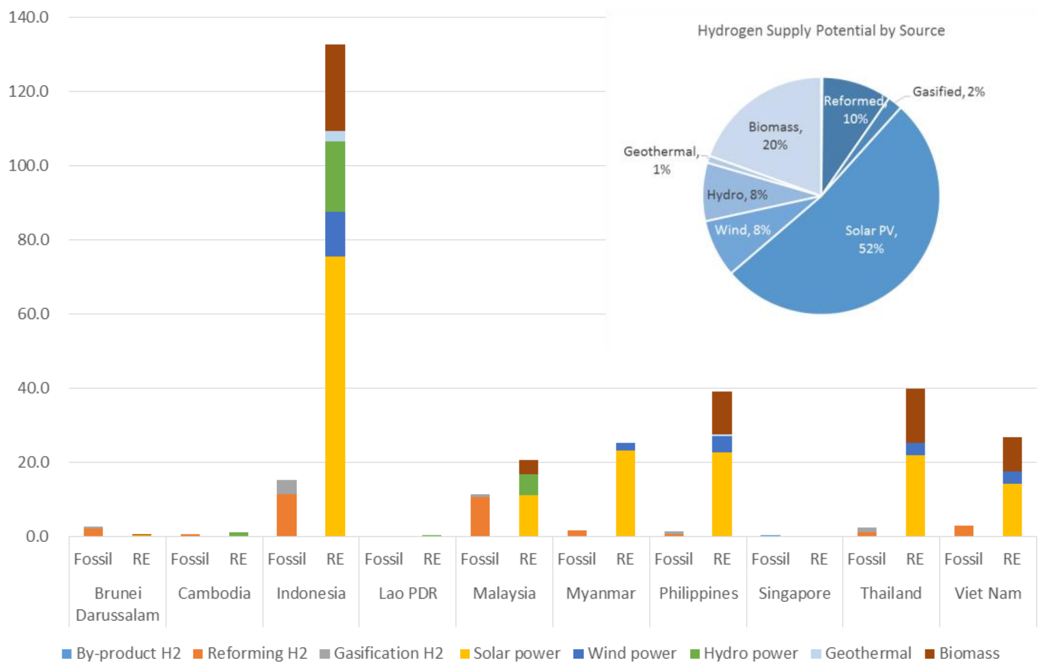


Mtoe = million tonnes of oil equivalent, PV = photovoltaics, RE = renewable energy.
Source: Author.

The Association of Southeast Asian Nations (ASEAN) region has the potential of 323 Mtoe of hydrogen, with Indonesia accounting for 46%, followed by Thailand and the Philippines, as shown in Figure 4.12.

As a source of hydrogen, renewable energy accounts for 90% of the group's supply potential and photovoltaics takes the largest share at 58%, followed by biomass gasification at 22%, then wind and hydraulic power. Amongst fossil fuel-derived hydrogen, reformed hydrogen takes the largest share at 83%, followed by gasified hydrogen, as compared to the Java and Sumatra region.

Figure 4.12 Hydrogen Production Potential in 2040 (ASEAN)



Lao PDR = Lao People's Democratic Republic, PV = photovoltaics, RE = renewable energy.
Source: Author.

1.3.3. Hydrogen Production Forecast

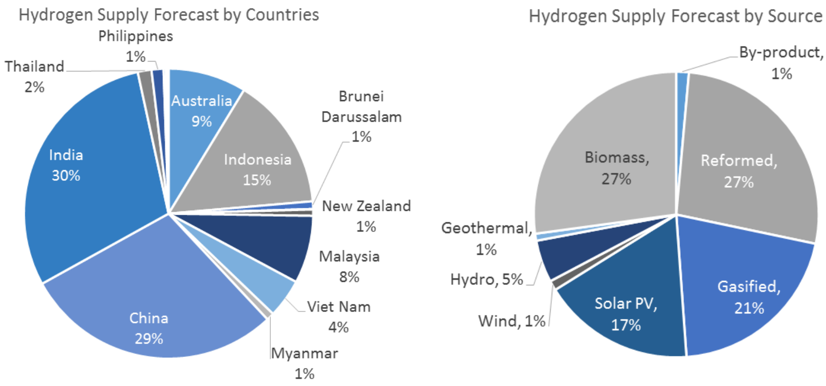
With rapid economic and demographic growth in the EAS region, along with global trends for renewables and decarbonisation, hydrogen is expected to play a key role in the transition away from fossil fuels through its mid- and long-term storable and transportable capability in this region.

In terms of the hydrogen supply forecast in 2040, the EAS region can reach 154 Mtoe, with India and China taking the largest share of around 30% each. They also have a high demand forecast themselves, with each able to satisfy its own domestic demand, as shown in Figure 4.13.

Indonesia (including Sumatra, Java, and other Eastern regions) and Australia will follow those countries in the majority of its hydrogen production being for export.

Regarding hydrogen sources, production derived from reformed gas and biomass will each account for 27%, followed by gasified liquids and solids.

Figure 4.13 Hydrogen Supply Forecast by Countries and Source



PV = photovoltaics.
Source: Author.

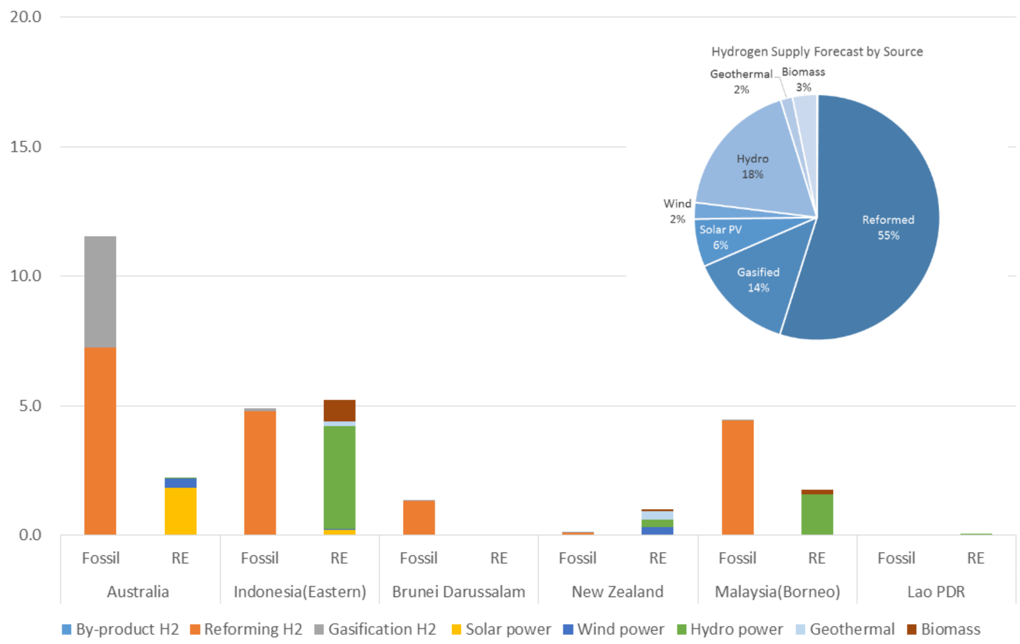
The hydrogen supply forecast in the Exporting group can reach 32.4 Mtoe in 2040, with Australia accounting for 42%, followed by the Eastern regions of Indonesia with 31%, then the Borneo region of Malaysia with 20%, as shown in Figure 4.14.

Fossil fuel-derived hydrogen shares 68% of the total supply forecast, including gas reforming and lignite gasification. It is necessary to investigate available locations and technology for CCUS, in case of hydrogen production from gas and lignite. The amount of hydrogen produced from flare gas and as a by-product is relatively small and is projected to be allocated for domestic supply or as an export supplement.

Hydro will take more than the half of the share of renewable energy-derived hydrogen, followed by photovoltaics with 20%. The volume of photovoltaic- and wind power-derived hydrogen will potentially increase as the result of innovations in water electrolysis.

Major hydrogen sources in Australia, the largest hydrogen-producing country in the Exporting group, consist of 53% gas, 31% lignite, and 13% photovoltaics. As the second-largest hydrogen-producing region, the Eastern regions of Indonesia will produce hydrogen mainly from gas, accounting for 47%, followed by hydro power with 39%, and biomass with 8%.

Figure 4.14 Hydrogen Production Forecast in 2040 (Exporting Group)



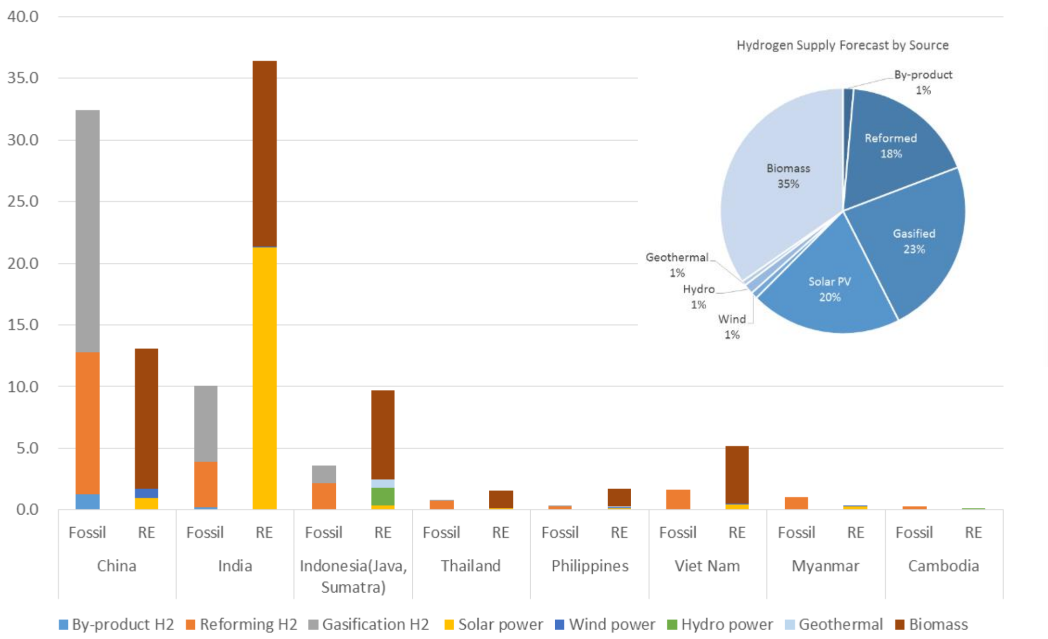
Lao PDR = Lao People's Democratic Republic, PV = photovoltaics, RE = renewable energy.
Source: Author.

Amongst Intra-regional group countries, the hydrogen supply forecast can reach 118Mtoe in 2040, with India accounting for 39%, followed by China with 38%, as shown in Figure 4.15.

In terms of hydrogen source, renewables accounts for 57%, with biomass gasification taking more than the half of the share, followed by photovoltaics with 35%. Reformed hydrogen from mid-small gas fields accounts for 42% amongst fossil fuel-derived hydrogen, followed by lignite gasification with 40%.

As the largest supplier of hydrogen in this group, India shows a forecast of 47 Mtoe of hydrogen in 2040, mostly from renewables, with photovoltaics accounting for 46%, followed by biomass gasification with 32%. As the second-largest supplier, China shows a forecast of 45 Mtoe of hydrogen, mostly from lignite gasification, accounting for 31%, followed by biomass gasification and gas reforming with 25% each.

Figure 4.15 Hydrogen Production Forecast in 2040 (Intra-regional Group)



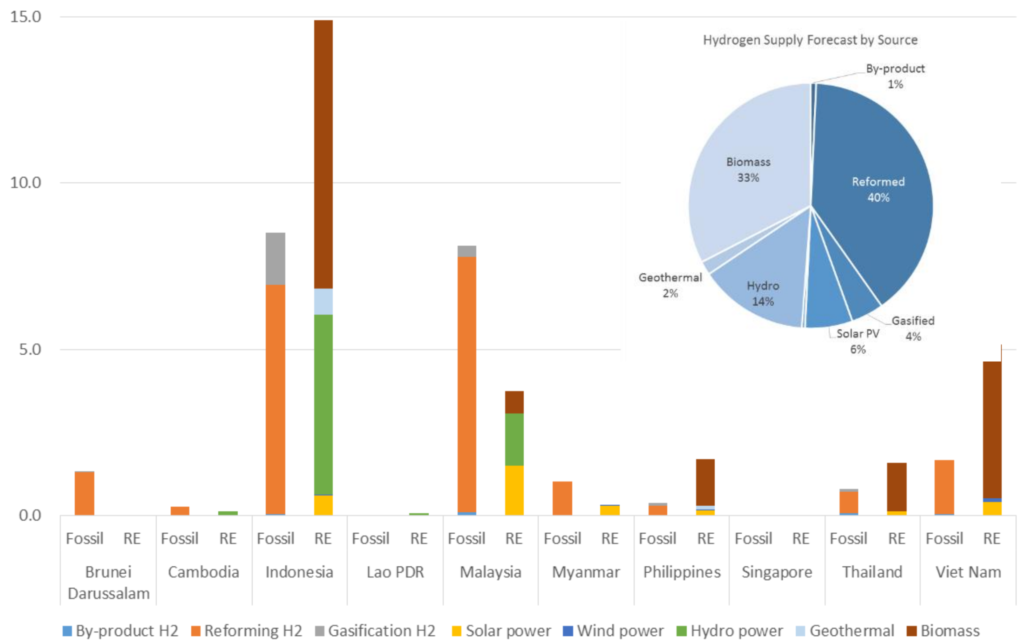
PV = photovoltaics, RE = renewable energy.
Source: Author.

The ASEAN region has a forecast of 50 Mtoe of hydrogen in 2040, with Indonesia accounting for almost the half of the share, followed by Malaysia with 24%, as shown in Figure 4.16.

Renewables derived hydrogen accounts for 56% of the total, with biomass gasification taking the largest share at 59%, followed by hydropower with 26%, then photovoltaics with 11%. Within fossil fuel-derived hydrogen, gas-reformed hydrogen accounts for the largest share with 89%. More research is needed about available location and technology for CCUS, in case of hydrogen production from gas and lignite.

As the largest supplier of hydrogen, Indonesia shows a forecast of 23 Mtoe of hydrogen, with biomass gasification accounting for 32%, followed by reformed hydrogen with 29%, then hydro with 23%. As the second-largest supplier, Malaysia has a forecast of 12 Mtoe, with gas-derived hydrogen taking the largest share at 65%, followed by hydro with 13% and photovoltaics with 13%.

Figure 4.16 Hydrogen Production Forecast in 2040 (ASEAN)



Lao PDR = Lao People's Democratic Republic, PV = photovoltaics, RE = renewable energy.
Source: Author.

1.3.4. Summary of Hydrogen Production: Potential vs. Forecast

In general, hydrogen production potential, at 1,876 Mtoe, has enough volume to fulfil the forecast for 2040 of 154 Mtoe that will be balanced with expected demand. Exporting countries will cover the gap between supply and demand in Importing countries and Intra-regional countries will fulfil their own domestic demand, as shown in Table 4.7.

In Exporting countries, Australia will potentially be the largest hydrogen exporter in the EAS region, followed by Indonesia.

In Intra-regional countries, India and China have the largest hydrogen production potential.

Importing countries have less hydrogen production potential compared with demand; therefore, the hydrogen production forecast is equal to its potential.

Table 4.7 Hydrogen Production Potential and Forecast in 2040 (by Group)

Group	Country	H2 Forecast (mtoe/y)			H2 Potential (mtoe/y)		
		Fossil Fuel	Clean Energy	TOTAL	Fossil Fuel	Clean Energy	TOTAL
I. Exporting	Australia	11.5	2.2	13.7	95.8	727.4	823.2
	Indonesia (Eastern)	4.9	5.2	10.1	10.0	111.2	121.2
	Malaysia (Borneo)	4.4	1.8	6.2	7.6	18.5	26.0
	Brunei Darussalam	1.3	0.0	1.3	2.5	0.4	2.9
	New Zealand	0.1	1.0	1.1	0.2	7.7	7.9
	Lao PDR	0.0	0.1	0.1	0.0	0.1	0.1
II. Intra-regional	China	32.4	13.1	45.5	54.5	69.6	124.0
	India	10.1	36.4	46.5	15.9	581.6	597.5
	Indonesia (Java, Sumatra)	3.6	9.7	13.3	5.0	21.4	26.5
	Viet Nam	1.7	5.2	6.8	2.7	26.7	29.5
	Thailand	0.8	1.6	2.4	2.3	39.9	42.2
	Philippines	0.4	1.7	2.1	1.3	39.1	40.4
	Myanmar	1.0	0.3	1.4	1.7	25.2	26.9
	Cambodia	0.3	0.1	0.4	0.4	1.1	1.6
III. Importing	Japan	0.1	0.0	0.1	0.1	0.0	0.1
	Republic of Korea	0.3	0.0	0.3	0.3	0.0	0.3
	Malaysia (Peninsula)	2.1	0.0	2.1	3.7	2.0	5.7
	Singapore	0.0	0.0	0.0	0.0	0.0	0.0
TOTAL		**75.2**	**78.4**	**153.6**	**204.1**	**1,671.9**	**1,876.0**

Lao PDR = Lao People's Democratic Republic, Mtoe/y = million tonnes of oil equivalent per year.
Source: Author.

In the ASEAN region, Indonesia will potentially be the largest hydrogen exporter, and Malaysia will follow, as shown in Table 4.8.

Thailand, the Philippines, Viet Nam, and Myanmar have enough hydrogen production potential to fulfil their forecast in 2040, which will be balanced with their expected demand.

Lao PDR has a large hydropower potential for export due to its inland location, and potentially can utilise hydrogen to store or absorb seasonal or mid-long-term supply variations.

Table 4.8 Hydrogen Production Potential and Forecast in 2040 (by ASEAN and Others)

Group	Country	H2 Forecast (mtoe/y)			H2 Potential (mtoe/y)		
		Fossil Fuel	Clean Energy	TOTAL	Fossil Fuel	Clean Energy	TOTAL
I. ASEAN	Brunei Darussalam	1.3	0.0	1.3	2.5	0.4	2.9
	Cambodia	0.3	0.1	0.4	0.4	1.1	1.6
	Indonesia	8.5	14.9	23.4	15.0	132.6	147.6
	Lao PDR	0.0	0.1	0.1	0.0	0.1	0.1
	Malaysia	6.5	1.8	8.3	11.2	20.5	31.7
	Myanmar	1.0	0.3	1.4	1.7	25.2	26.9
	Philippines	0.4	1.7	2.1	1.3	39.1	40.4
	Singapore	0.0	0.0	0.0	0.0	0.0	0.0
	Thailand	0.8	1.6	2.4	2.3	39.9	42.2
	Viet Nam	1.7	5.2	6.8	2.7	26.7	29.5
TOTAL (ASEAN)		20.6	25.7	46.3	37.2	285.7	322.9
II. Others	Australia	11.5	2.2	13.7	95.8	727.4	823.2
	China	32.4	13.1	45.5	54.5	69.6	124.0
	India	10.1	36.4	46.5	15.9	581.6	597.5
	Japan	0.1	0.0	0.1	0.1	0.0	0.1
	Republic of Korea	0.3	0.0	0.3	0.3	0.0	0.3
	New Zealand	0.1	1.0	1.1	0.2	7.7	7.9
TOTAL (Others)		54.6	52.7	107.3	166.9	1386.3	1553.1
TOTAL		75.2	78.4	153.6	204.1	1671.9	1876.0

ASEAN = Association of Southeast Asian Nations, Mtoe/y = million tonnes of oil equivalent per year.
Source: Author.

2. Hydrogen Transportation

2.1. Hydrogen Transportation Method and Portfolio

Hydrogen transportation methods consist of transportation modes and hydrogen carriers.

Typical transportation modes include ships, railways, road freight, and pipelines. Major hydrogen carriers are liquid hydrogen (LH_2), ammonia (NH_3), organic hydride (MCH), and compressed hydrogen (CH_2), as shown in Figure 4.17.

Hydrogen can be liquefied at -253 °C and the volume of hydrogen gas will be converted to 1/800 as liquid, the technology for which has already been commercialised in smaller local hydrogen supply chains. However, LH_2 has an energy-intensive liquefaction process and boil-off loss should be considered.

Hydrogen can also be transported as NH_3, which is already produced and transported globally, with the volume of hydrogen gas being converted to 1/1,300 liquid. However, NH_3 is toxic and transporting hydrogen requires dehydrogenation technology.

Finally, hydrogen can be transported as a chemical by reacting it with Toluene to form MCH, which is transported as a liquid under ambient conditions using existing infrastructure. MCH converts hydrogen gas to 1/500 liquid and requires relatively higher temperature for dehydrogenation.

Figure 4.17 Hydrogen Transportation Method

< Transportation mode >

- **Ship transportation**
  Liquid H2 tanker, Chemical tanker, Container vessel, Barge, etc.
- **Railway transportation**
  Freight train, Container train, etc.
- **Truck transportation**
  Liquid H2 truck, Chemical / Gasoline tank truck, Tube trailer for compressed gas, etc.
- **Pipeline transportation**
  Hydrogen gas pipeline, Natural gas pipeline, etc.

< Hydrogen Carrier >

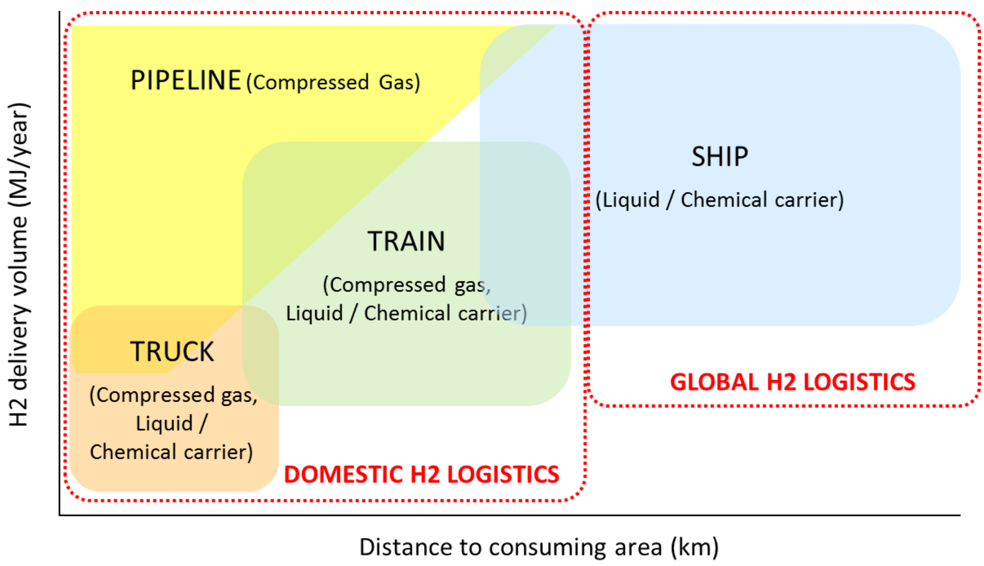
	Liquid Hydrogen (LH2)	Ammonia (NH3)	Chemical Hydride (MCH)	Compressed Hydrogen (CH2-700MPa)
Molecular Weight	2.0	17.0	98.2	2.0
H2 Content (wt%)	100	17.8	6.2	100
Volumetric H2 Density (kg-H2/m3)	70.8	121.0	47.4	39.6
Boiling Point (deg-C)	-253	-33.4	101	-
H2 Release Enthalpy Change (kJ/mol-H2)	0.9	30.6	67.5	-
Others	- High purity - Low energy to be pressurised	- High H2 density - Direct combustion	- Liquid at ambient - Utilize existing oil infrastructure	- Widely used in existing market

Source: Author.

Transportation modes and hydrogen carriers can be selected and combined based on the hydrogen delivery volume, distance and characteristic of each transportation mode/carrier, as shown in Figure 4.18.

Global hydrogen logistics will use tanker ships for long-distance transportation, and domestic hydrogen logistics will combine ships, rail, trucks, and pipelines with proper carriers depending on delivery volume and distance.

Figure 4.18 Image of Hydrogen Logistics Portfolio



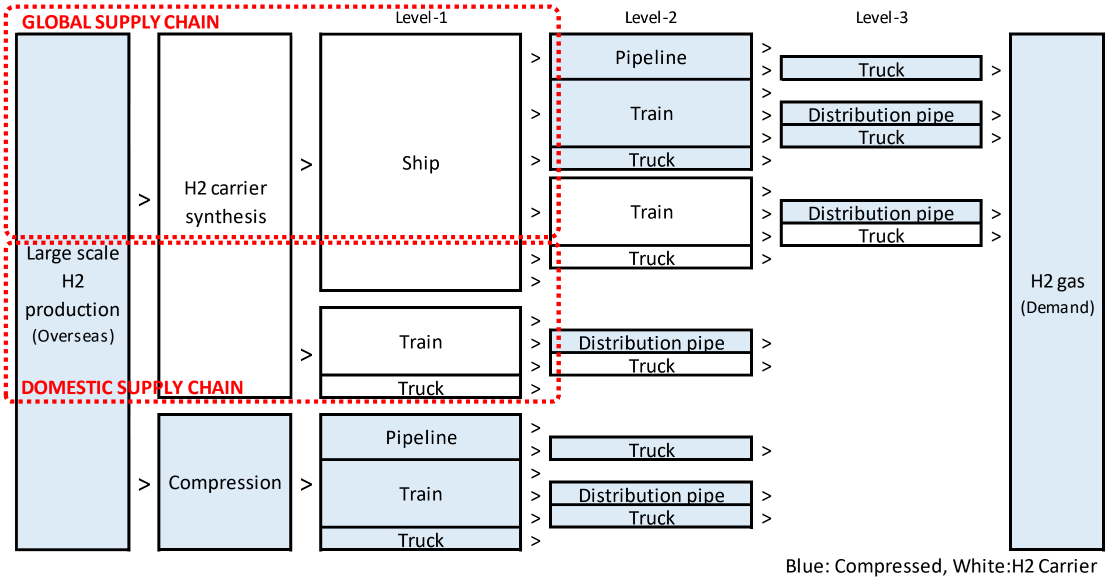
Source: Author.

Several hydrogen logistics scenarios can be drafted via the combination of transportation modes/hydrogen carriers and volume of hydrogen production/demand.

This study analyses the case of large-scale hydrogen production with larger concentrated demand for global supply chains and smaller distributed demand for domestic supply chains, as shown in Figure 4.19.

To consider the flexibility of hydrogen logistics networks, especially in early stages of hydrogen commercial deployment, this study focuses on interchangeable modes of transportation, such as ships, trains, and trucks.

Figure 4.19 Hydrogen Logistics Scenario for Large-scale Production



Source: Author.

2.2. Hydrogen Transportation Cost

The study includes three hydrogen transportation pathways, LH_2, NH_3, and MCH. The transportation cost (not including the cost of carrier synthesis from H_2 gas to carrier and H_2 regeneration from H_2 carrier to gas) dependency on the transportation distance (km) for the selected carriers is shown in Figure 4.21 to Figure 4.23.

In general, CH_2 transportation is more economical for shorter transportation distances and smaller volume, as compared with other hydrogen carriers. Figure 4.20 compares the hydrogen delivery cost between CH_2 and LH_2 by transportation distance and volume.

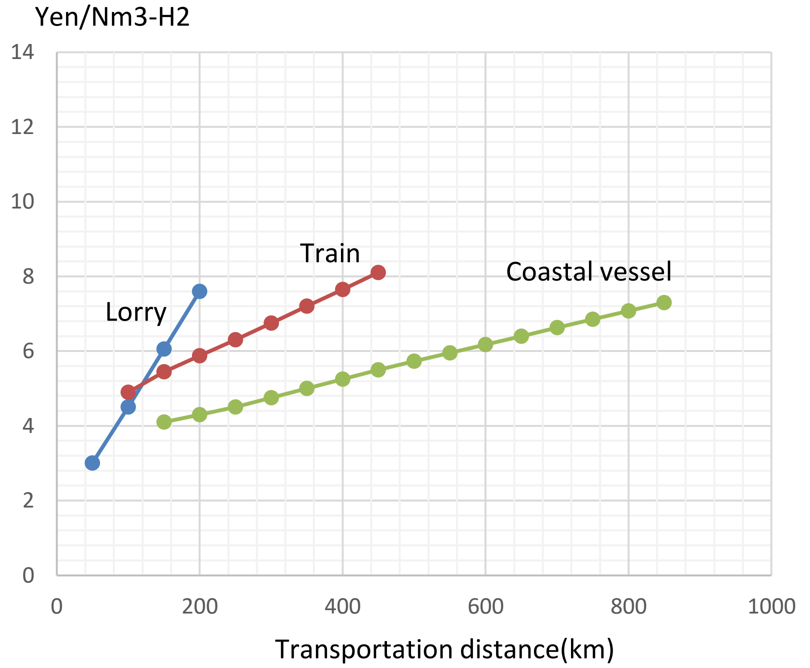
Figure 4.20 Example of Hydrogen Delivery Cost of CH_2 and LH_2 (US Department of Energy)

FCEV = fuel cell electric vehicle.
Source: Elgowainy (2018).

2.2.1. Hydrogen Transportation by Liquid Hydrogen (LH_2)

The transportation cost of LH_2 appears relatively high, as the cost of cryogenic equipment is much higher than other carriers. A transportation distance of around 100km is a reverse point between trucks and trains. Coastal vessels have the cheapest transportation cost above 100km.

Figure 4.21 General Transportation Costs by Truck, Train, and Ship (LH_2)

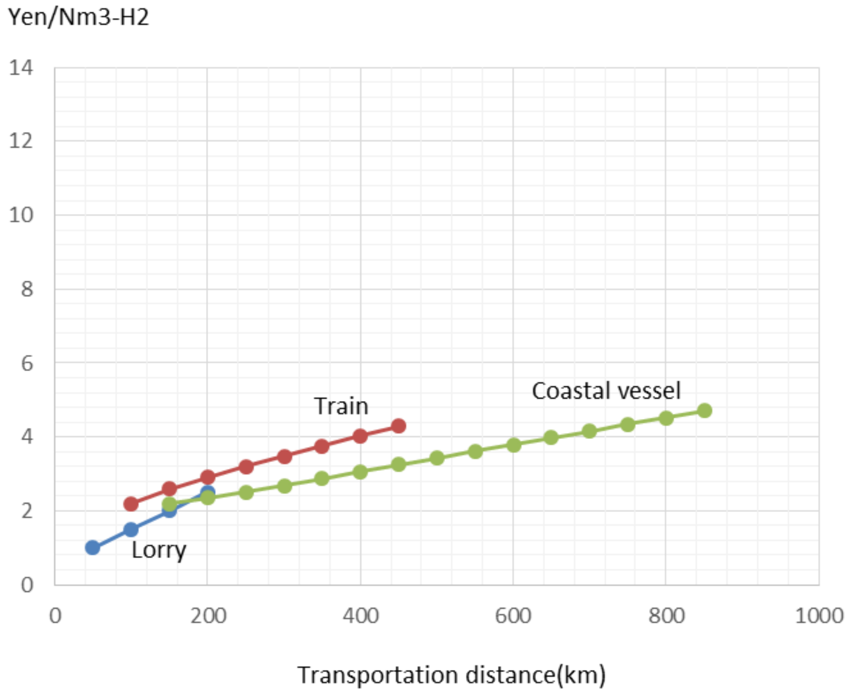


Note: The data were customised based on Institute of Applied Energy (2016).
Source: Author.

2.2.2. Hydrogen Transportation by Ammonia (NH_3)

The transportation cost of NH_3 shows relatively lower dependency on the distance. Also, the cost difference amongst three modes is the smallest.

Figure 4.22 General Transportation Costs by Truck, Train, and Ship (NH_3)

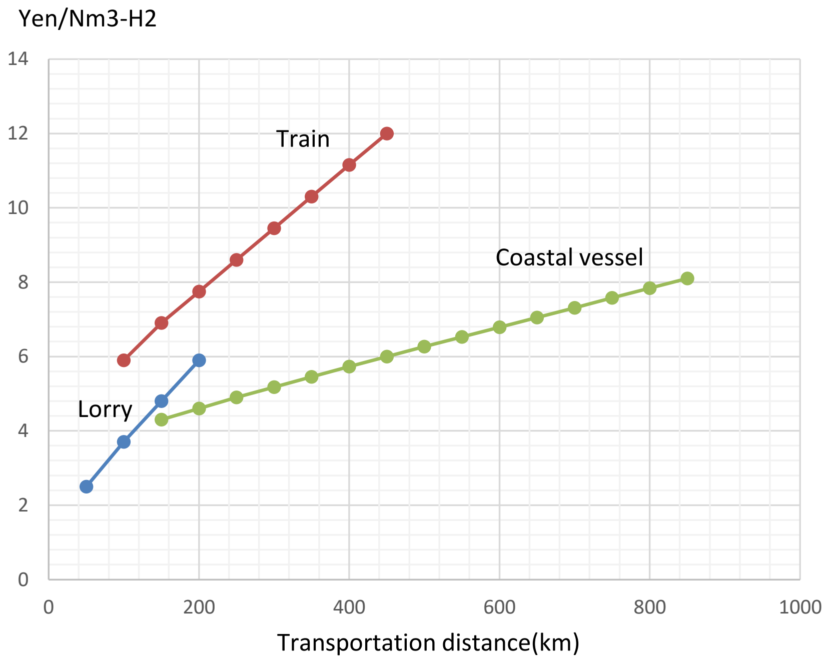


Note: The data were customised based on Institute of Applied Energy (2016).
Source: Author.

2.2.3. Hydrogen Transportation by Chemical Hydride (MCH)

MCH shows transportation costs as high as those of LH_2, because MCH has less hydrogen content per weight compared to other carriers. The transportation distance of around 120km is a reverse point between truck and coastal vessel.

Figure 4.23 General Transportation Costs by Truck, Train, and Ship (MCH)



Note: The data were customised based on Institute of Applied Energy (2016).
Source: Author.

3. Hydrogen Supply Chain and Its Cost

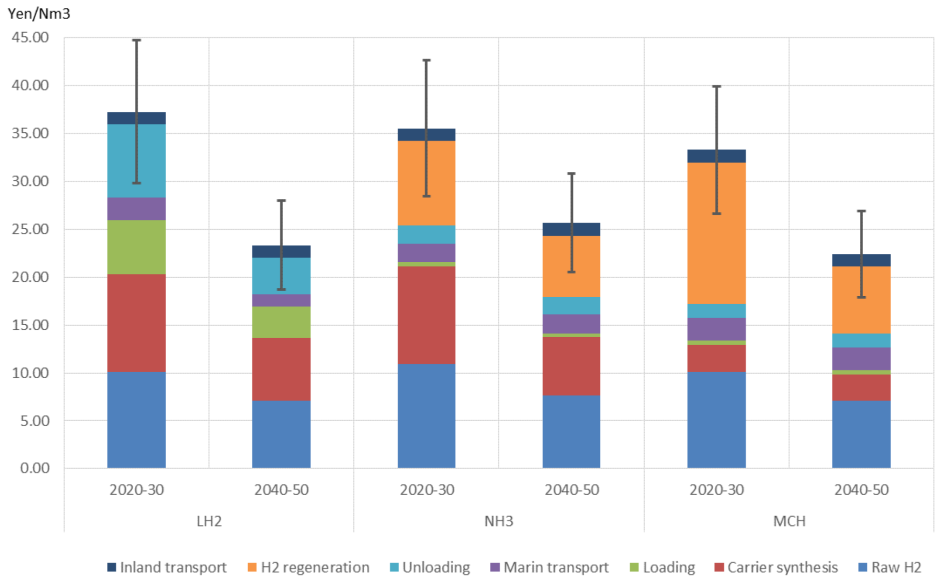
3.1. Global Hydrogen Supply Chain Cost

Figure 4.24 shows an example of global hydrogen supply cost for large-scale production (2.5 billion Nm^3/year) to Japan from exporting countries in this region in 2020–30 and 2040–50, respectively.

For the cost components of global hydrogen supply chains, marine transportation is minor for all carriers; carrier synthesis and unloading are major components of the LH_2 supply chain, carrier synthesis and H_2 regeneration are major components of the NH_3 supply chain, and H_2 regeneration is a major component of the MCH supply chain.

Each hydrogen carrier has merit and technical challenges, and requires continuous technology development to accelerate cost reductions. In developing the hydrogen transportation infrastructure, it is also necessary to consider the balance between the future goals and the longer-term uncertainties of technological achievement.

Figure 4.24 An Example of Global Hydrogen Supply Cost to Japan (5,400 km)

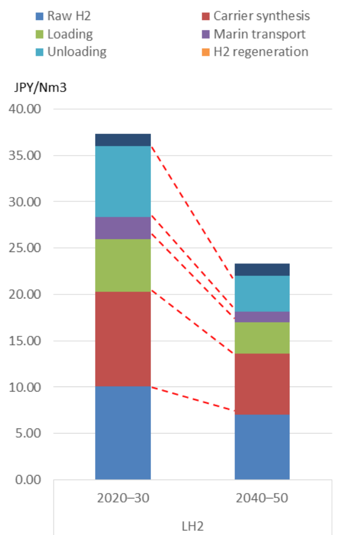


Note: The data were customised based on Institute of Applied Energy (2016).
Source: Author.

3.1.1. LH_2 Cost Reduction Scenario

Key points for reducing the cost of LH_2 transportation are to achieve higher liquefaction performance, minimisation/utilisation of boil-off gas, and upscaling, as shown in Figure 4.25.

Figure 4.25 Cost Down Scenario of Liquid Hydrogen (LH_2)



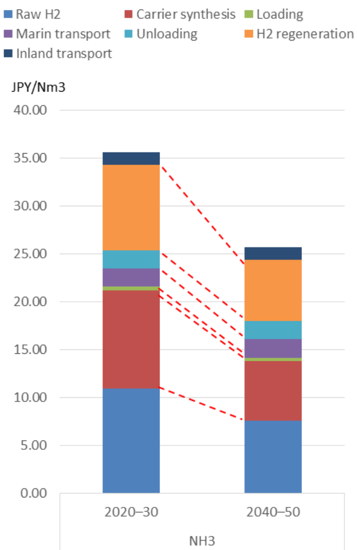
Process	Cost down scenario
H2 regeneration	• Large scale LH2 vaporiser (~400 tonne/d class)
Unloading	• Large scale LH2 tank with lower BOG (200,000m3 with BOR 0.1%/d) • Effective utilization of cold heat of LH2 • Larger & efficient LH2 loading arm
Marine transportation	• Large sized LH2 transportation vessel (with minimum BOG)
Loading	• Larger & efficient LH2 loading arm • Large scale LH2 transfer pump (~3,000m3/h) • Higher efficiency of BOG compressor
Carrier synthesis	• Higher efficiency of liquefaction process (Liquefying machine of 100-300 tonne/d with power consumption < 0.60 kWh/Nm3)

BOG = boil-off gas, BOR = boil-off rate, JPY = Japanese yen,
Note: The data were customised based on Institute of Applied Energy (2016).
Source: Author.

3.1.2. NH_3 Cost Reduction Scenario

Key points for reducing NH_3 transportation costs are to achieve higher ammonia synthesis performance, development of NH_3 decomposition technology, and upscaling, as shown in Figure 4.26.

Figure 4.26 Cost Down Scenario of NH_3



Process	Cost down scenario
H2 regeneration	• Develop Larger & efficient NH3 decomposition technology and plant (2,400 tonne/d class)
Unloading	• Large-scale NH3 storage tank (50,000 tonne class)
Marine transportation	• Large-scale NH3 transportation vessel (38,000 m3 class)
Loading	• Large-scale NH3 storage tank (50,000 tonne class)
Carrier synthesis	• NH3 synthesis plant with higher efficiency (1,600 tonne/d class, post Haber–Bosch process)

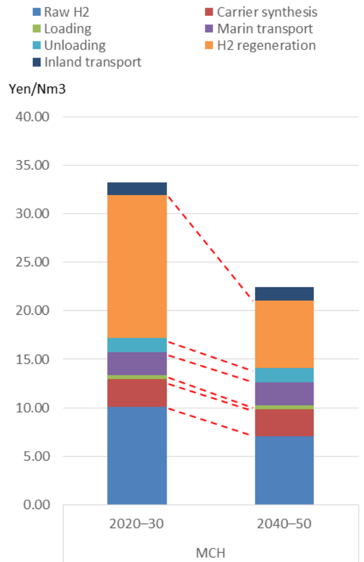
Note: The data were customised based on Institute of Applied Energy (2016).

Source: Author.

3.1.3. MCH Cost Reduction Scenario

Key points for reducing the cost of MCH are to achieve higher dehydrogenation performance, effective utilisation of hydrogenation process heat, and upscaling, as shown in Figure 4.27.

Figure 4.27 Cost Down Scenario of MCH



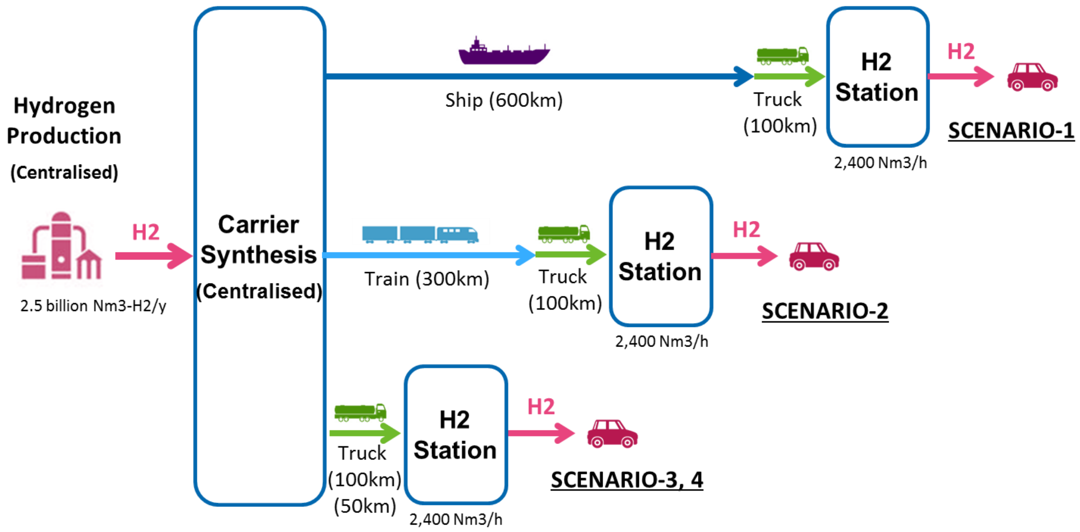
Process	Cost down scenario
H2 regeneration	• Larger scale dehydrogenation (DHG) plant (>1,000,000Nm3/h) • Decreasing in reaction temperature • Higher performance of DHG catalyst • Integration of DHG reaction with exhaust heat
Unloading	
Marine transportation	• Large scale transportation vessel (100,000m3 class - chemical tanker)
Loading	
Carrier synthesis	• Larger scale hydrogenation (HGN) plant (>1,000,000Nm3/h) • Effective utilization of process heat from HGN

Note: The data were customised based on Institute of Applied Energy (2016).
Source: Author.

3.2. Local Hydrogen Supply Chain Cost

To understand each technological step in local hydrogen supply chains, Figure 4.28 applies the following four scenarios to study the costs from large-scale production sites (2.5 billion Nm^3/year) to refueling stations by each carrier (LH_2, NH_3, and MCH).

Figure 4.28 Typical Scenarios for Local Hydrogen Supply Chain



Source: Author.

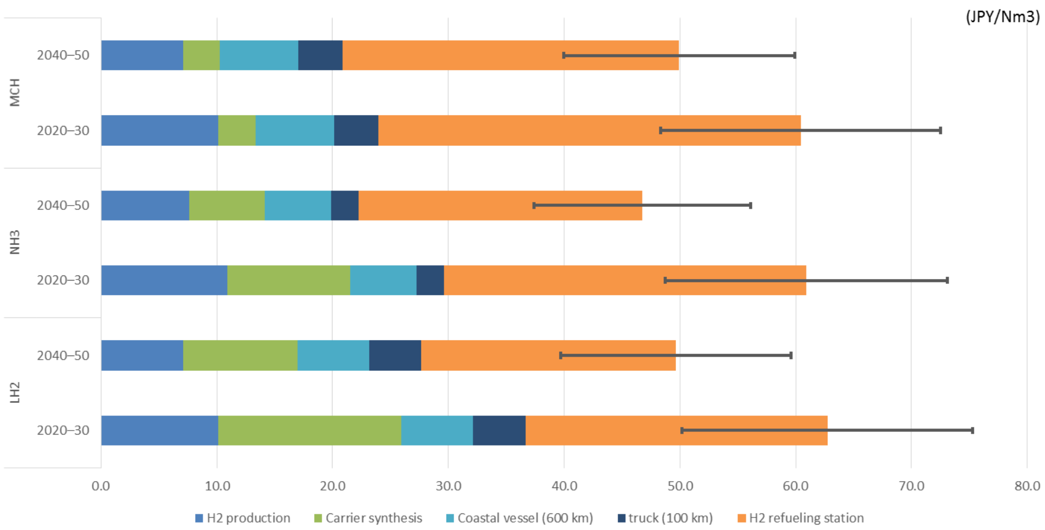
The cost of large-scale hydrogen production (raw hydrogen) and synthesis for each carrier is taken from Figure 4.24. Each carrier is synthesised using different processes, i.e. hydrogen liquefaction, ammonia synthesis and hydrogenation of Toluene. Also, each carrier uses each regeneration process, that is, liquid hydrogen vaporisers, ammonia decomposition, and dehydrogenation of MCH. These processes will be customised to improve energy efficiency for 2040–2050.

3.2.1. Local Hydrogen Supply Chain Cost of Scenario-1 (Ship + Truck)

Figure 4.29 shows an example of the costs of a local hydrogen supply chain using the selected carriers. The costs include the use of large-scale hydrogen production and carrier synthesis, coastal vessel transport of 600km, truck transport of 100km, and hydrogen refuelling stations (scenario-1). In 2020–2030, the costs for MCH and NH_3 will be lower than LH_2 and the cost of NH_3 is expected to be the lowest in 2040–2050.

The black line on the right-hand edge of each cumulative bar shows an accuracy range of ±20%.

Figure 4.29 An Example of Local Hydrogen Supply Chain Cost (Scenario-1)



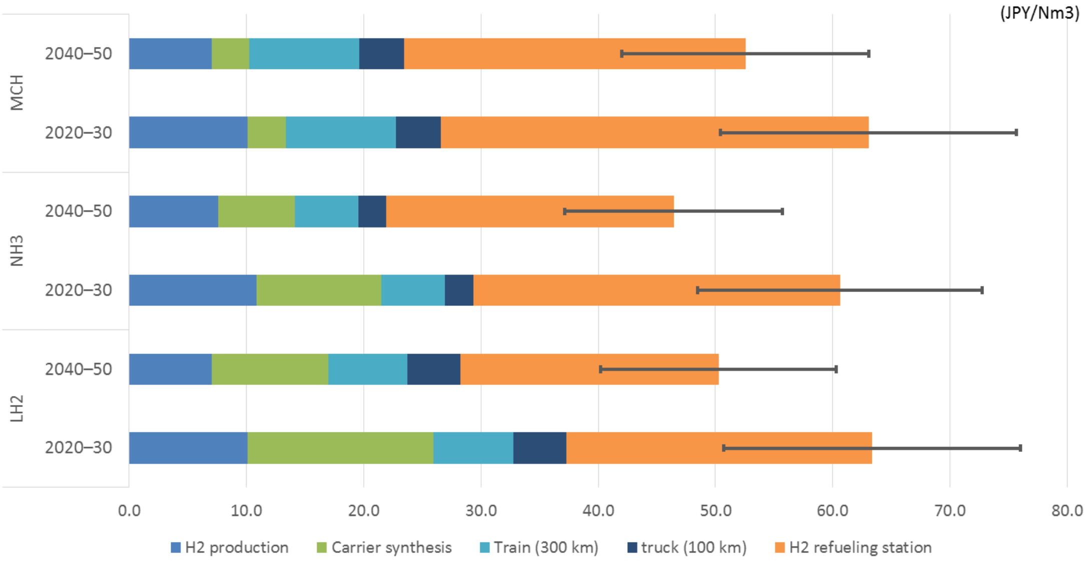
Note: The data were customised based on the Institute of Applied Energy (2016).
Source: Author.

3.2.2. Local Hydrogen Supply Chain Cost of Scenario-2 (Train + Truck)

In Figure 4.30, the costs include the use of large-scale hydrogen production and carrier synthesis, train transport of 300km, truck transport of 100km, and hydrogen refuelling stations (scenario-2).

The costs of MCH and LH_2 are the same and NH_3 also shows the lowest cost in 2020–2030 and 2040–2050.

Figure 4.30 An Example of Local Hydrogen Supply Chain Cost (Scenario-2)



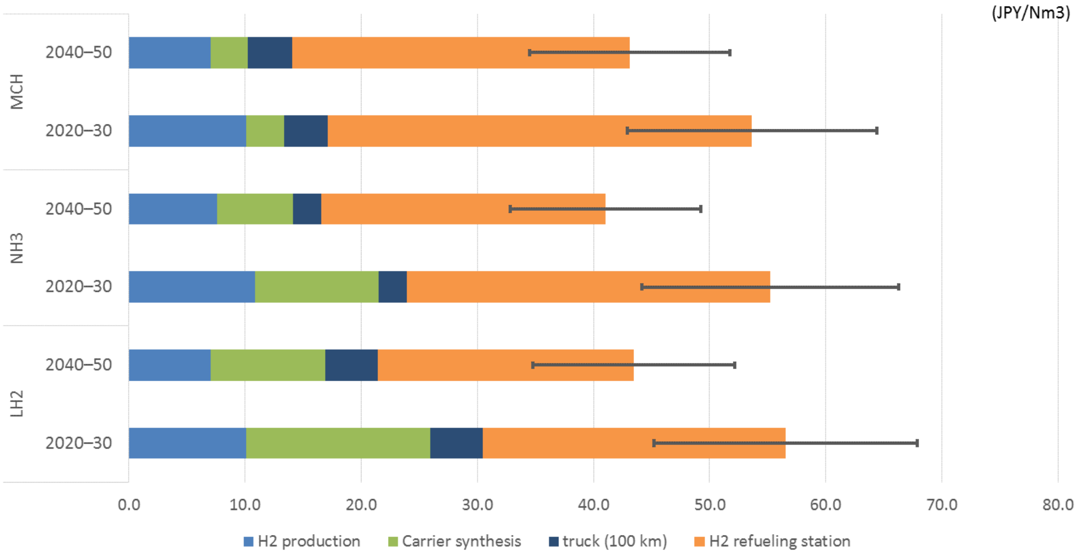
Note: The data were customised based on the Institute of Applied Energy (2016).
Source: Author.

3.2.3. Local Hydrogen Supply Chain Cost of Scenario-3 & 4 (Truck)

In Figure 4.31, the costs include the use of large-scale hydrogen production and carrier synthesis, truck transport of 100km and hydrogen refuelling stations (scenario-3). The costs are in the order of MCH, NH_3, and LH_2 from the lowest in 2020–2030, and NH_3 will be the lowest cost in 2040–2050.

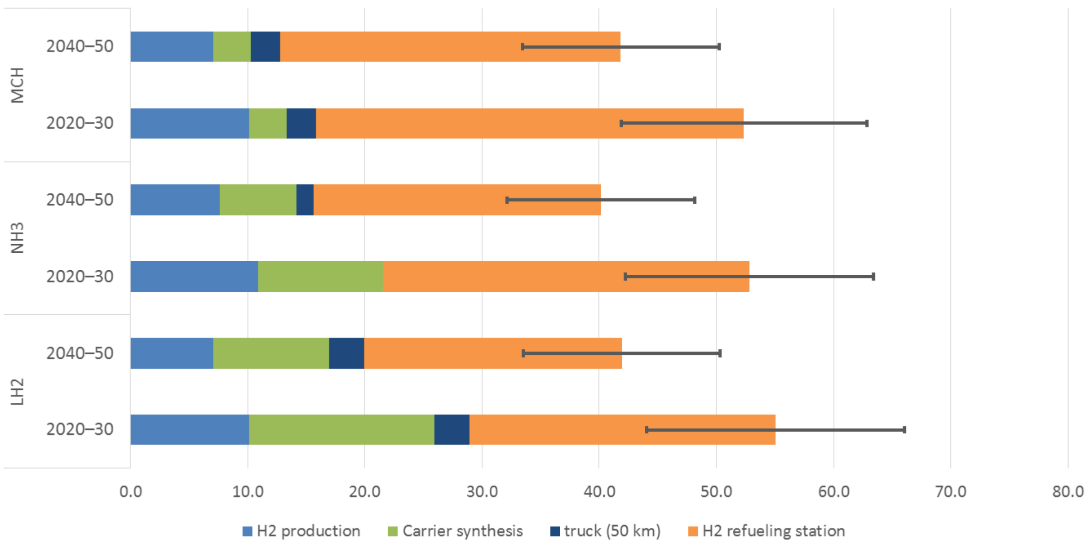
Figure 4.32 shows same transportation scenario with 50km truck transport (scenario-4). The costs of the selected carriers are the same trend of scenario-3.

Figure 4.31 An Example of Local Hydrogen Supply Chain Cost (Scenario-3)



Note: The data were customised based on the Institute of Applied Energy (2016).
Source: Author.

Figure 4.32 An Example of Local Hydrogen Supply Chain Cost (Scenario-4)



Note: The data were customised based on the Institute of Applied Energy Report.(8)
Source: Author.

Summary

3.3. Hydrogen production and transportation

3.3.1. Hydrogen supply and demand balance in the EAS region

Hydrogen demand and supply in the EAS region is expected to be well balanced between 'Exporting' and 'Importing' and inside 'Intra-regional' countries in 2040. Exporting countries have enough potential to export to Importing countries, and Intra-regional countries have also enough potential, though some countries will require imports depending on the demand growth.

Table 4.9 Summary of Hydrogen Production and TPES in 2040 (by Group)

Group	Country	H2 TPES (mtoe/y)			H2 Production (mtoe/y)		Difference (F-S3)
		Scenario 1	Scenario 2	Scenario 3	Forcast	Potential	
I. Exporting	Australia	1.5	3.5	5.7	13.7	823.2	8.0
	Indonesia (Eastern)	0.9	2.0	3.3	10.1	121.2	6.8
	Malaysia (Borneo)	0.3	0.7	1.2	6.2	26.0	5.0
	Brunei Darussalam	0.1	0.1	0.2	1.3	2.9	1.1
	New Zealand	0.1	0.3	0.5	1.1	7.9	0.6
	Lao PDR	0.0	0.0	0.1	0.1	0.1	0.0
II. Intra-regional	China	11.8	27.7	45.5	45.5	124.0	0.0
	India	13.4	29.3	46.5	46.5	597.5	0.0
	Indonesia (Java, Sumatra)	3.5	8.0	13.3	13.3	26.5	0.0
	Viet Nam	2.0	4.3	6.8	6.8	29.5	0.0
	Thailand	0.7	1.5	2.4	2.4	42.2	0.0
	Philippines	0.6	1.3	2.1	2.1	40.4	0.0
	Myanmar	0.3	0.8	1.4	1.4	26.9	0.0
	Cambodia	0.1	0.2	0.4	0.4	1.6	0.0
III. Importing	Japan	3.7	8.4	13.3	0.1	0.1	-13.1
	Republic of Korea	2.7	5.8	8.9	0.3	0.3	-8.7
	Malaysia (Peninsula)	1.2	2.9	4.8	2.1	5.7	-2.7
	Singapore	0.2	0.5	0.7	0.0	0.0	-0.7
TOTAL		**43.3**	**97.3**	**157.1**	**153.6**	**1,876.0**	**-3.6**

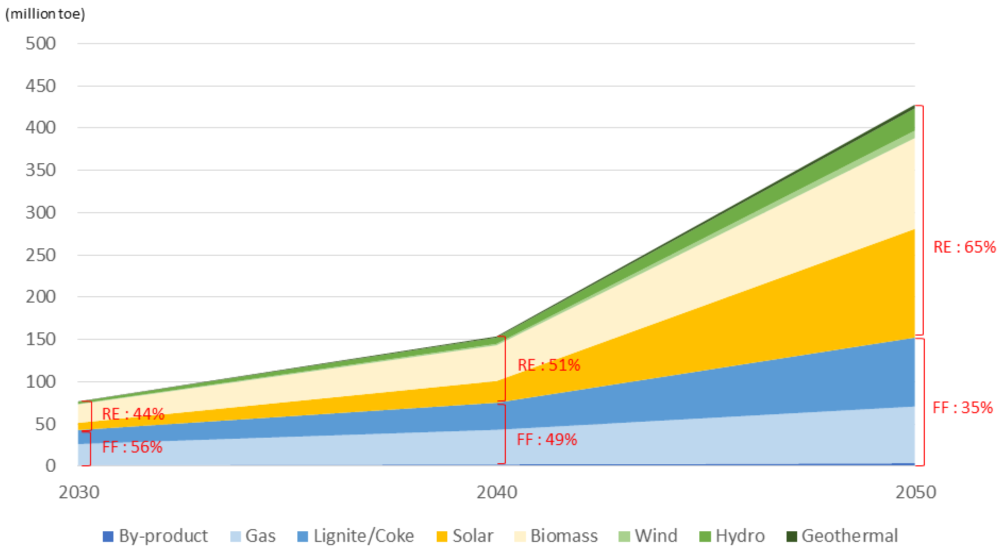
Lao PDR = Lao People's Democratic Republic, TPES = total primary energy supply.
Source: Author.

3.3.2. Transition of hydrogen production sources

Our forecast shows that a major hydrogen source will be from fossil fuels with stable hydro/geothermal and partial solar/wind, mainly for local consumption in early stages. Sources will largely shift to abundant renewable energy as the result of technological development, as shown in Figure 4.33.

The supply potential from economical hydrogen sources, such as gas or stable renewable energy, is limited, and hydrogen from abundant solar, wind, biomass, lignite/coal will increase, along with technological improvements for each hydrogen production method, including water electrolysis and CCUS.

Figure 4.33 Image of Hydrogen Production Source Transition in the EAS Region



EAS = East Asia Summit, FF = fossil fuels, RE = renewable energy.
Source: Author.

3.3.3. Global hydrogen supply chain and its network in the EAS region

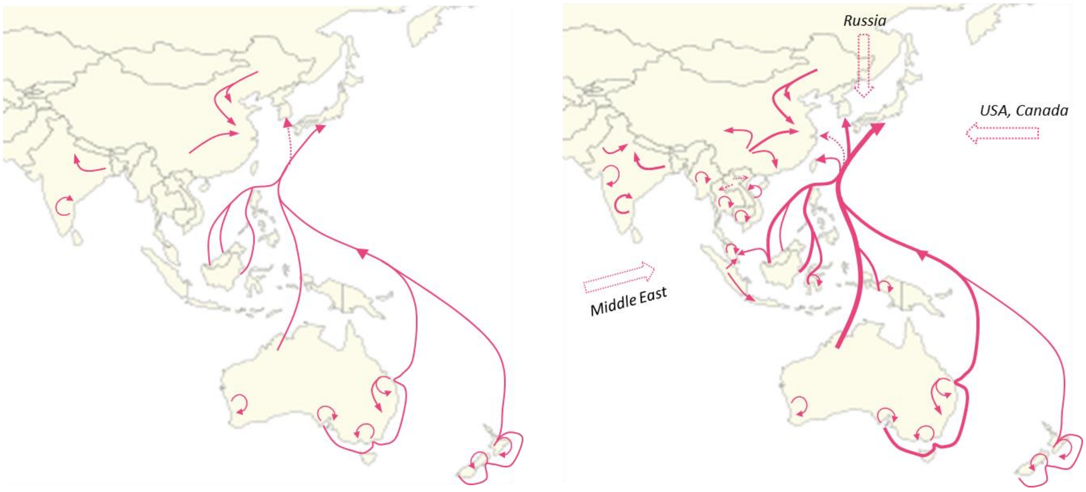
This study envisions that, in the early stage (2020–2030), global trading of hydrogen from exporting countries to Japan, Republic of Korea, and local supply chains in China, India, and some other countries will be started.

Those supply chains are expected to be widely spread out in the EAS region, and linked to an eventual global hydrogen energy network, including trading to other countries outside this region, in 2040–2050.

Figure 4.34 shows images of the future hydrogen trade flow in the EAS region.

Figure 4.34 Image of Hydrogen Trade Flows in the EAS Region

2020–2030 **2040–2050**



Source: Author.

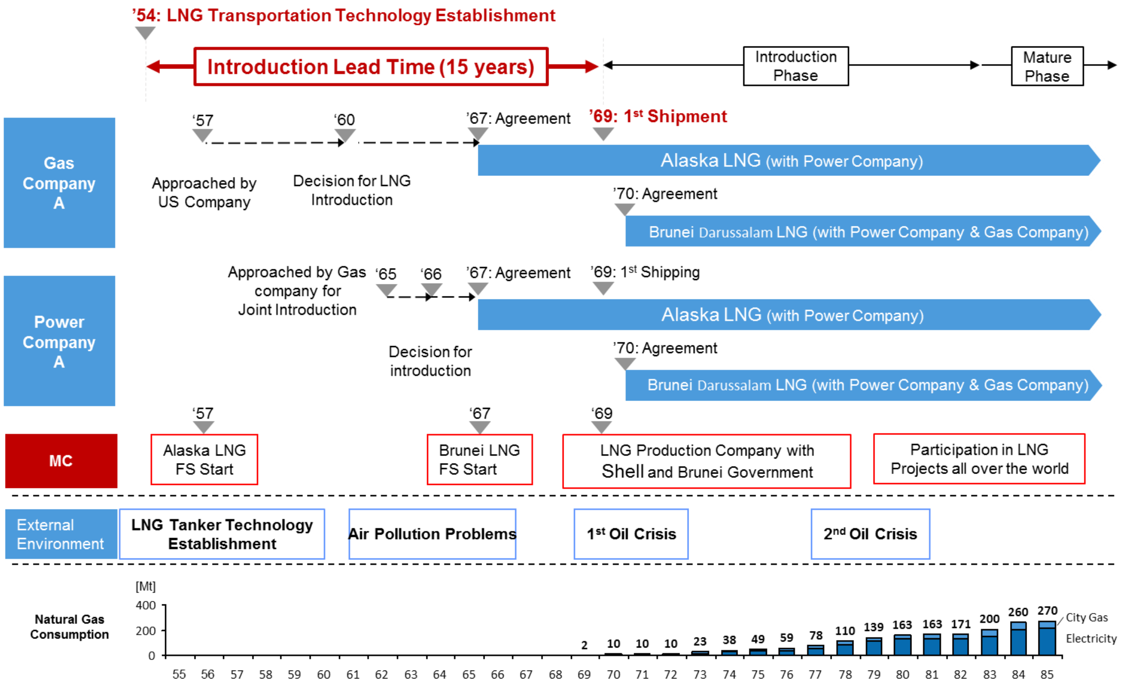
3.4. Hydrogen market creation

3.4.1. History of LNG imports to Japan

In the case of the LNG business, it took 15 years for the first LNG shipment to be made once the transportation technology was established in 1954, and over 30 years to mature the market, as shown in Figure 4.35.

Hydrogen will also be assumed to take time to develop, penetrate, and mature its market.

Figure 4.35 History of LNG Import Business to Japan



FS = feasibility study, MC = Mitsubishi Corporation, LNG = liquefied natural gas.
Source: Mitsubishi Corporation.

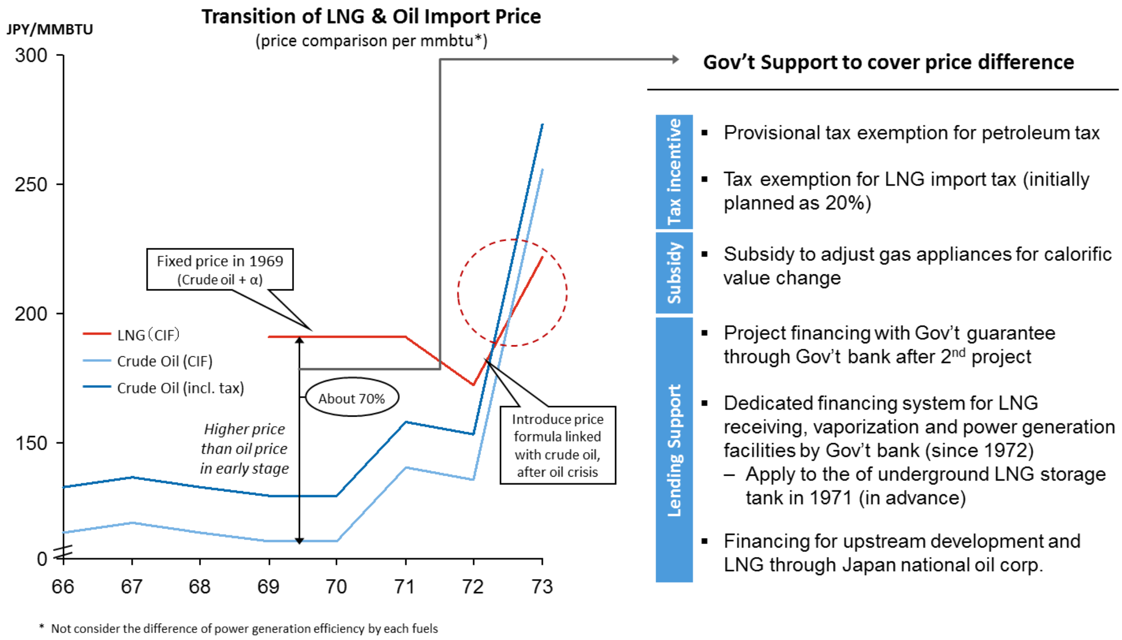
3.4.2. History of LNG import prices to Japan

LNG was introduced to improve air pollution in Japan; however, the price was quite high compared to the oil price in the 1960s and early 1970s, before the oil crisis.

Under this circumstance, the Japanese government introduced LNG, including tax incentives, a subsidy, and lending support.

This means that government support is one of the key areas to introduce hydrogen into the market, especially in early stages.

Figure 4.36 History of LNG and Oil Import Prices to Japan



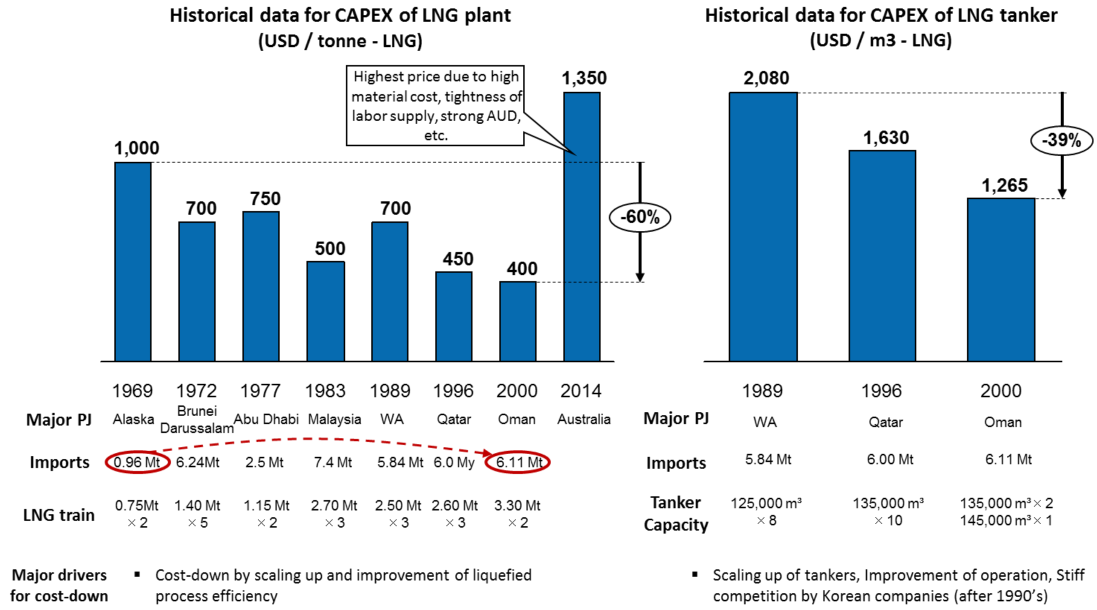
CIF = cost insurance freight, JPY = Japanese yen, LNG = liquefied natural gas.
Source: Mitsubishi Corporation.

3.4.3. History of LNG production and transportation cost

LNG production and transportation costs have been reduced by technological developments and upscaling over the last 30 years.

These are the same key factors for reducing hydrogen supply chain costs.

Figure 4.37 History of LNG Plant and Tanker Costs



AUD = Australian dollar, CAPEX = capital expenditure, LNG = liquefied natural gas, PJ = project, WA = Western Australia.
Source: Mitsubishi Corporation.

3.5. Hydrogen policy implications

3.5.1. Hydrogen policy implications in the EAS region

Proposed policy implications regarding the global hydrogen market and supply chain in the EAS region are shown in Figure 4.38.

National approaches, including strategies, government support, and awareness programmes, will develop hydrogen in each country, and regional approaches will enhance the interconnection and trading between each country in this region.

Figure 4.38 Hydrogen Policy Implications in the EAS region

National Approach

1. **National hydrogen strategy and roadmap**

Develop technical, marketing, and business strategy to introduce hydrogen into the national energy market.

2. **Government support**

Introduce financial support (tax incentives, subsidy, lending support, etc.) and market mechanisms (carbon trading, etc.) in early stages..

3. **Awareness programme**

Enlighten the key organisations and public to have common understandings of the meanings, benefits, and challenges of introducing hydrogen into the market.

Regional Approach

1. **Standardisation** (refer to next two pages)

Develop standard to evaluate/label carbon reduction value of hydrogen, and define hydrogen price/volume unit for global trading and statistics, and develop technology/safety standard in this region.

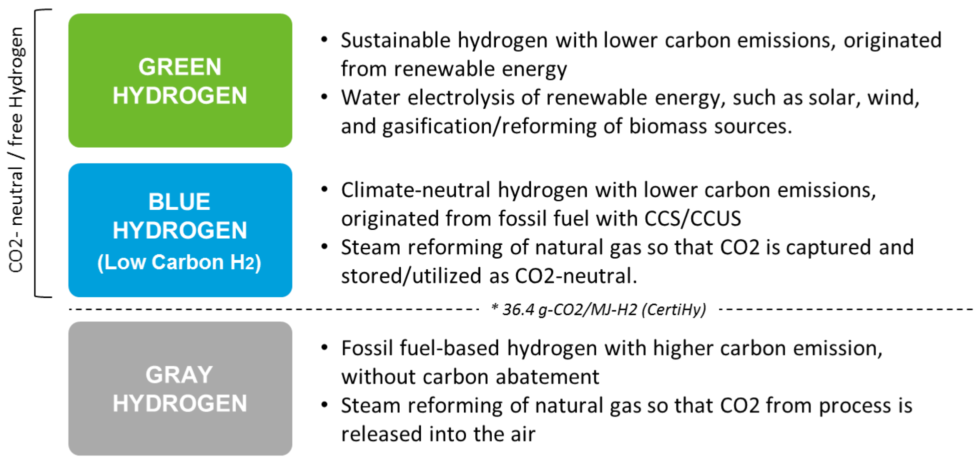
EAS = East Asia Summit.
Source: Author.

3.5.2. *Example of standardisation-1 (Carbon reduction value)*

Low carbon emissions is one of the key values of hydrogen, making it necessary to set up international standards to evaluate/define carbon reduction values for global trading.

The EU introduced a hydrogen certification system that is categorised into three groups based on their sources and CO_2 emissions. This will be a valuable reference to establish the standard in this region and to align with other regions.

Figure 4.39 Definition of Green/Low-Carbon Hydrogen in EU



CCS/CCUS = carbon capture and storage/carbon capture, utilisation, and storage, EU = European Union.
Source: Hinichio and Hinichio (2016); GasTerra (2018).

3.5.3. Example of standardisation-2 (Trading & statistic unit)

At present, there is no global hydrogen market, and unified trading and statistical units are not available.

It is necessary to define hydrogen price/volume unit for its global trading and statistics that are commonly utilised and understood in this region.

Figure 4.40 Trading and Statistic Unit for Hydrogen and Other Energy

Energy Market

- Oil : \$/bbl
- LNG : \$/mmbtu, \$/tonne
- Gas : \$/mmbtu, \$/Nm3 or cf, \$/MWh
- Coal : \$/tonne
- Power : \$/MWh, ¢/kWh

Energy Statistics

- MJ
- kWh
- Kcal
- TOE (tonne of oil equivalent)
- BOE (barrel of oil equivalent

Heating Value

- HHV (Gross)
- LHV (Net)

What is the proper unit for hydrogen trading and statics ?

Market Price

- ¢ / Nm3
- \$ / tonne
- \$ / mmbtu.

,etc.

Statistical Volume

- TOE
- BOE
- Nm3
- Tonne
- MJ / GJ / TJ / PJ

. etc.

Source: Author.

3.6. Conclusion

3.6.1. Shift hydrogen source from fossil fuel to renewable energy, and expand its network widely in the EAS region

- There are enough potentials to supply hydrogen to satisfy demand in this region, including trading from exporting countries to importing countries.
- In early stages, the major hydrogen source will be fossil fuels with hydrogen from stable hydro/geothermal; this will largely shift to abundant renewable energy, such as solar, wind, biomass as the result of technological and market development.
- Hydrogen supply chains will be assumed to start from exporting countries to Japan, Republic of Korea, with some local supply chains in China, India, and will expand its network globally and locally in this region in 2040–2050.

3.6.2. It is important to start actions now to develop a hydrogen market in the EAS region

- As shown by the history of LNG, it will take time to build the hydrogen market in this region.

- To meet the CO_2 abatement target (two-degree scenario) of the Paris Agreement, it is quite important to start actions now vis-à-vis R&D/technology development in hydrogen supply/utilisation, investment for hydrogen infrastructure, and collaborating with countries in this region.

3.6.3. Government support is one of the key drivers, especially in early stages

- Intensive support from governments shows the future vision regarding funding and market support mechanisms, R&D promotion, awareness programmes, etc.
- In addition, it is important to develop a standard for hydrogen trading globally in this region, including proper energy trading and statistical units and carbon reduction values.

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Chapter 5

Energy Consumption, Carbon Emissions, and Hydrogen Supply Chain and Fuel Cell Electric Vehicle Costs in ASEAN Countries

1. Motivation and Methodology

Commercialisation of hydrogen as an alternative to fossil fuels is still economically challenging. According to the US Department of Energy, the cost of hydrogen production from centralised or distributed electrolysis in 2015 was US$3–$3.9/kg, short of the targeted cost of $2/kg.[1]

Questions remain as to whether deployment of hydrogen-based powertrains, namely fuel cell electric vehicles (FCEVs), for ASEAN countries' passenger car, bus, and truck fleets can be reasonably justified, given the technological outlook. If not, it is worth understanding how big the economic gaps of hydrogen supply chains are, and from what parts of the supply chain they stem. This will also inform which FCEV application niches could be prioritised, as they are most likely to become competitive in the near future.

Specifically, this study aims to model the well-to-wheel (WTW) energy, carbon emissions, and cost profile of a hydrogen supply chain. In addition, at the user end of hydrogen applications, as a fuel for the land transport sector, the energy consumption, carbon emissions, and economics will be analysed as against alternatives, including conventional fossil fuels for internal combustion engine vehicles (ICEVs), as well as battery-based electric vehicles (BEVs). A total cost of ownership (TCO) concept will be applied in this regard.

WTW and TCO models that cover both the upstream and downstream of the hydrogen economy will be developed using Excel Macro, capable of simulating various scenarios, assuming different technologies, industrial processes, environmental parameters, resource endowments, market setups, and energy and industrial policies. Reasonable assumptions about these key factors will be able to precisely indicate the economic and environmental feasibility of hydrogen supply chains, as well as a hydrogen economy.

2. A Review of Past WTW and TCO Studies on Hydrogen Supply Chains

Ally and Pryor (2016) conducted a TCO analysis, applying a lifecycle assessment framework on the application of fuel cell buses (FCBs) compared to diesel, compressed natural gas, and hybrid buses, operated between 2012 and 2014 in Australia. The study found that at the current level of capital and operation costs and with current performances of hydrogen and fuel cell technologies, the TCO of an

[1] source: https://www.energy.gov/eere/fuelcells/doe-technical-targets-hydrogen-production-electrolysis

FCB is 2.6 times that of a conventional diesel bus. Even if the US Department of Energy's long-term targets (Spendelow and Papageorgopoulos, 2012) about FCB capital and operating expenditure are achieved, a gap of A$400,000+ between the two technologies' TCO would remain. The study assumed that the cost of hydrogen is between A$20.90/kg and A$22.40/kg, if the electricity cost is A$0.26/kWh and small-scale on-site production is applied. At such TCO levels, FCBs cannot compete with either hybrid or compressed natural gas buses (compressed natural gas bus TCOs are 36% higher than those for a diesel bus, due to high cost of natural gas). However, if diesel prices increase to A$4.5/L from the current level of A$1.388/L, FCBs' TCO can break even with that of diesel buses, at A$19/kg. Capital expenditure, followed by the cost of hydrogen, is the largest driver of FCBs' TCO. It is noted that this study assumed no FCB end-of-life value after the assumed 15 years' usage.

An earlier WTW study by Cockroft and Owen (2007) considered the external value of environmental impacts by various powertrain technologies for urban buses, taking as a case study the bus fleet in Perth, Australia. This study assumes an initial capital cost of the hydrogen FC bus as about 29% higher than conventional diesel buses, which cost US$418,400 each, a very aggressive assumption following the US Department of Energy's long-term targets of US$30/kW for fuel cell stacks and an average of US$15/kW of complementary infrastructure cost. It also assumed an idealistic cost of hydrogen fuel at US$5/kg. With such favourable assumptions for hydrogen FC buses, there is still a gap of US$265,800 between the net present value of the total private cost of operation for the 15-years lifetime of a diesel bus and that of a hydrogen FCB. This gap can be reduced to US$169,000, when the social costs of urban air pollution, as well as climate change due to greenhouse gas (GHG) emissions, are considered. In more aggressive scenarios, in which either fossil fuel costs increase faster in future or the environmental costs surge to higher values, the gap can be bridged or even reversed.

A lifecycle cost analysis was conducted by Cockroft and Owen (2017), reporting the levelled cost of hydrogen, on a well-to-tank basis, from a real and small distributed water electrolysis project in Belgium, which produces hydrogen from wind power, as well as grid electricity. The reported data were collected up to 2015. The reported cost of hydrogen dispensed was EUR13.9/kg. The cost is mostly driven by feedstock, followed by capital and operational costs. This is compared to a range of costs varying from EUR2.8/kg to EUR27.5/kg documented in previous literature.

Nguyen et al. (2013) conducted a WTW analysis on the carbon emissions of mid-size light duty vehicles applying various powertrains in a 2035 scenario, covering ICEVs, hybrid vehicles, plug-in hybrid vehicles, range-extension electric vehicles, BEVs, and fuel cell electric vehicles (FCEVs). In the case of the first three, various fuel sources, including renewables with various blending levels are applied. FCEVs powered by hydrogen sourced from wind as well as biomass production pathways have the potential to deliver the lowest carbon emissions. This is followed by hydrogen produced from natural gas and coal with carbon capture. Plug-in hybrid vehicles and range-extension electric vehicles are amongst the second league in delivering lower carbon emissions, if biofuel and electricity from renewable sources are applied.

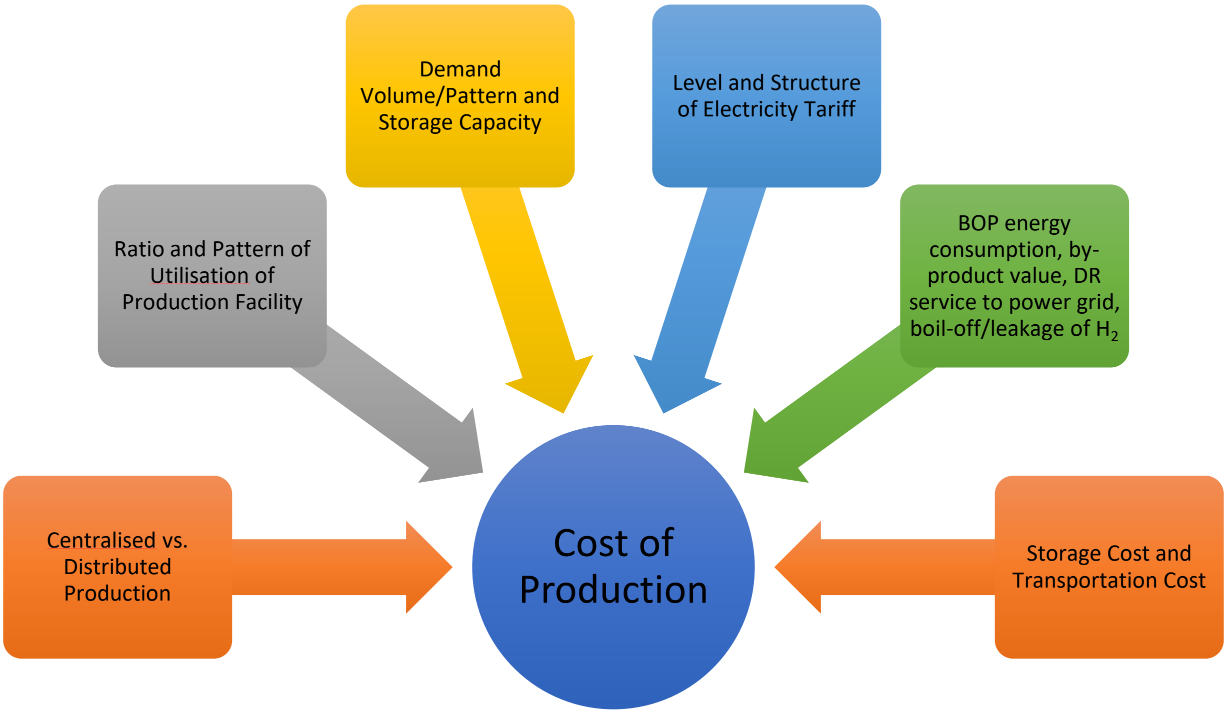
3. Model Description, Data, and Scenarios

3.1. General Description of the Model

This study builds a WTW model to capture the energy production and consumption process, as well as the costs and emissions involved. Based on the WTW concept, a TCO is further developed to access the cost of owning, as well as driving, a vehicle through its lifetime. The studied vehicle fleets include mid-size passenger cars, buses, and heavy-duty trucks.

Key factors determining the costs of hydrogen production pathways are modelled in Figure 5.1:

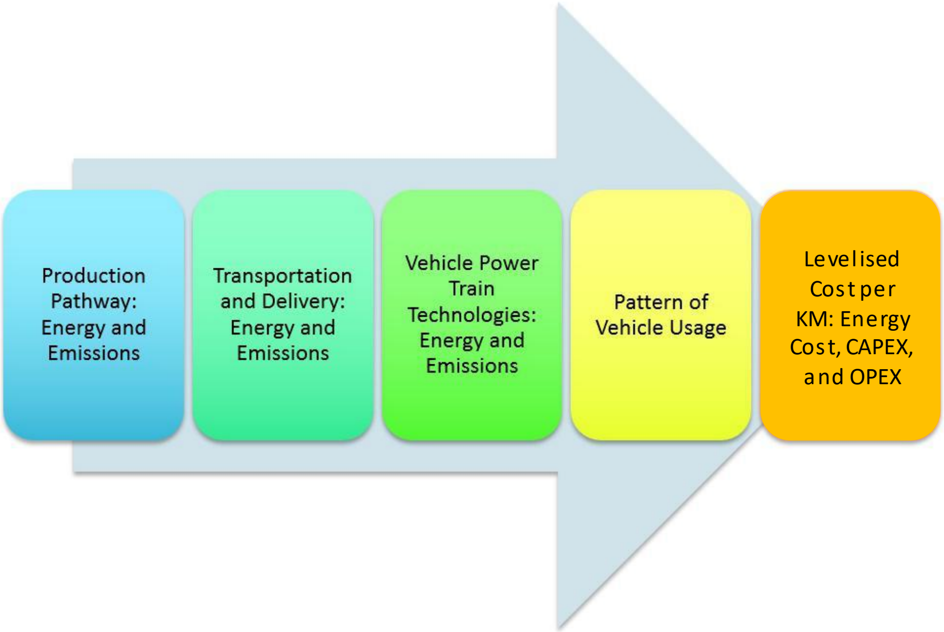
Figure 5.1 Key Factors Considered in Modelling the Hydrogen Production Pathways



BOP = balance of plants, DR = demand response.
Source: Authors.

Figure 5.2 shows the results of modelling the TCO of vehicles:

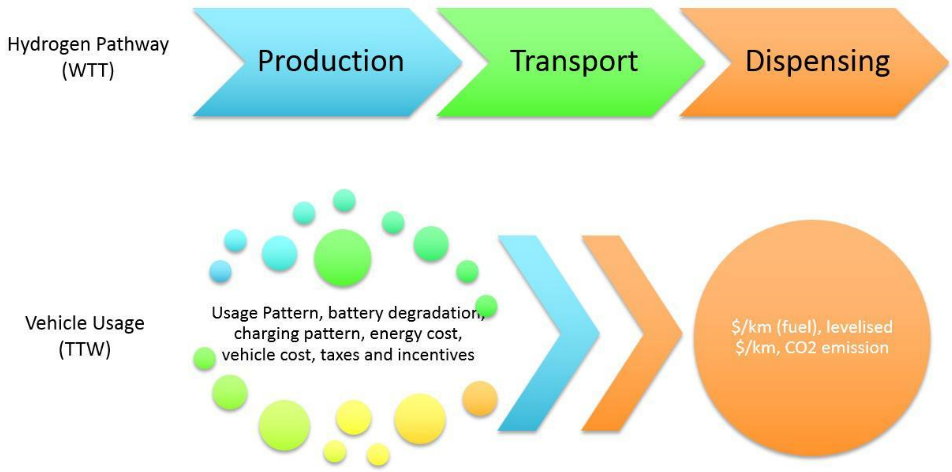
Figure 5.2 Key Factors Considered in Modelling the TCO of Vehicles



TCO = total cost of ownership, CAPEX = capital expenditure, OPEX = operating expenditure.
Source: Authors.

Figure 5.3 shows the relationship of between the WTW model and the TCO model. Basically, TCO is integrated into the TTW part of the WTW.

Figure 5.3 Well-to-Tank, Tank-to-Wheel, and Total Cost of Ownership



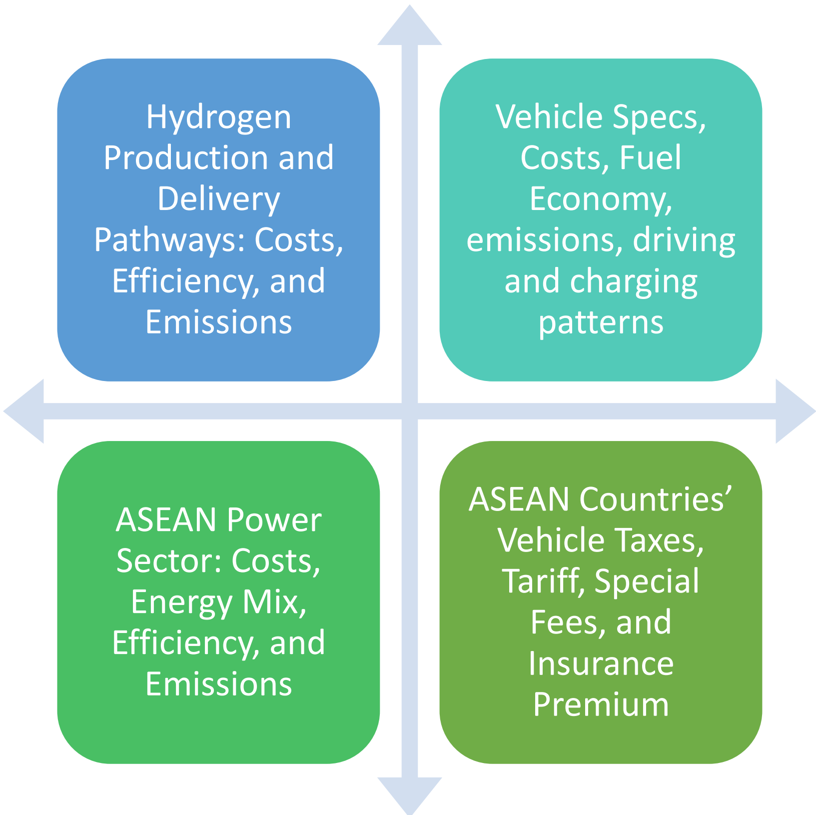
TTW = Tank-to-Wheel, WTT = Well-to-Tank.
Source: Authors.

3.2. Data Description

There are four major blocks of data inputs used in the models, as shown in Figure 5.4. The estimated production efficiency and costs of hydrogen pathways, as well as those for the transportation and dispensing of hydrogen, are collected from international sources, including US and Japan data. To apply the ASEAN countries' specific cases, the power generation sector is typically surveyed, covering the cost of electricity production, the energy mix, and GHG emissions of the power sector.

Data about vehicle specifications (such as engine size, battery size, and fuel cell stack size), costs and fuel economy are collected from international open market sources. To study the ASEAN countries' specific position in applying these vehicle technologies, data about the various vehicle taxes, tariffs, special fees, and insurance premiums are surveyed.

Figure 5.4 Four Major Blocks of Data Inputs



Source: Authors.

3.3. Scenarios

There are three dimensions along the hydrogen supply chain in which infrastructure changes will significantly influence both the costs and emissions level of the fuel. The first dimension is the choice of the mix of pathways, i.e., what percentage of the hydrogen supply is from which production pathway. The second dimension is the choice of the production mode, i.e., centralised or distributed (forecourt). The third dimension is the choice of the transportation and delivery network, i.e., the use of pipelines, compressed gas tube trailers, liquid tube trailers, with or without a storage function and gaseous or liquid hydrogen dispensing at a refuelling station. Accordingly, this study first creates a benchmark scenario, with fixed assumptions applying to all covered countries. This is followed by scenarios that vary from the benchmark, as a sensitivity test.

Since the technologies for both hydrogen supply chains and fuel cells are expected to go through significant breakthroughs in performance, as well as decreases in costs, future scenarios are also created to see how these developments will affect the competitiveness of hydrogen-based solutions for the road transport sector, as compared to other alternative powertrain solutions.

3.4. Benchmark Scenario

In the benchmark scenario, ASEAN countries are expected to apply a portfolio of hydrogen production as shown in Table 5.1, for both centralised and distributed pathways.

Table 5.1: Share of Pathways in the Benchmark Scenario (in %)

Country	Natural Gas Reforming	Lignite Gasification	Biomass Gasification	Solar PV	Wind
Brunei Darussalam	40	30	10	10	10
Cambodia	40	30	10	10	10
Indonesia	40	30	10	10	10
Lao PDR	40	30	10	10	10
Malaysia	40	30	10	10	10
Myanmar	40	30	10	10	10
Philippines	40	30	10	10	10
Thailand	40	30	10	10	10
Singapore	40	30	10	10	10
Viet Nam	40	30	10	10	10

Lao PDR = Lao People's Democratic Republic, PV = photovoltaics.
Source: Authors.

Regarding the choice of transportation and dispensing means, the benchmark results will have two variations. The first set of assumptions is to apply forecourt production with compressed gas dispensing, without storage. The second set is to apply centralised production with gaseous tube trailer transportation and compressed gas dispensing, with storage.

3.5. Sensitivity Analysis

As shown in Table 5.2, the comparative scenario assesses whether a higher share of renewables-based pathways could shift the relative competitiveness of FCEV powertrains against other alternative powertrains.

Table 5.2 Share of Pathways in the Alternative Scenario (in %)

Country	Natural Gas Reforming	Lignite Gasification	Biomass Gasification	Solar PV	Wind
Brunei Darussalam	25	15	20	20	20
Cambodia	25	15	20	20	20
Indonesia	25	15	20	20	20
Lao PDR	25	15	20	20	20
Malaysia	25	15	20	20	20
Myanmar	25	15	20	20	20
Philippines	25	15	20	20	20
Thailand	25	15	20	20	20
Singapore	25	15	20	20	20
Viet Nam	25	15	20	20	20

Lao PDR = Lao People's Democratic Republic, PV = photovoltaics.
Source: Authors.

To ensure comparability, the choice of transportation and dispensing means applies the same assumptions as in the benchmark scenario.

3.6. Future Scenarios

Future scenarios will separately check the capital cost outcome of FCEVs decreasing by 50% to 70%, that of the production cost of renewables-based pathways decreasing by 50%, and that of the transportation and dispensing costs also decreasing by 50%. These effects will be aggregated in this scenario to show the impacts of progresses in technology, as well as economies of scale and learning effects, by circa 2030. The expected changes in the prices of fossil fuel and grid electricity are also considered.

Regarding the choice of transportation and dispensing means, the future scenarios will also have two variations. The first set of assumptions is to apply forecourt production with compressed gas dispensing, without storage. The second set is to apply centralised production with liquid tube trailer transportation and liquid gas dispensing, with storage.

4. Simulation Results: Energy Consumption, Carbon Emissions, and Costs of FCEVs and Other Alternatives

4.1. Benchmark and Sensitivity Scenarios

This section summarises the results of the benchmark scenario, which compares the energy use, carbon emissions, and economics of the four different powertrains applied in each of the passenger car, bus, and truck fleets. In the scenario, forecourt and centralised hydrogen production are compared. This assumes that fossil fuels such as coal and natural gas dominate the production of hydrogen. All results of this scenario are then compared to a sensitivity scenario, in which renewables will dominate the production of hydrogen. Lastly, all results can be compared to those from the future scenario, in which the production cost of hydrogen, capital cost of FCEVs, and the costs of transportation and delivery of hydrogen are assumed to be 50% lower than the current levels by approximately 2030.

Table 5.3 presents the primary energy consumption per km, carbon emissions per km, TCO per km, as well as fuel cost per km of FCEVs consuming hydrogen produced from forecourt production, in comparison with those of the vehicles with alternative powertrains. The numbers presented are the outcome of an unweighted average of all ASEAN countries. Detailed results for each country are available upon request.

Table 5.3 Benchmark Scenario with Forecourt Production of Hydrogen: ASEAN Average Levels

		WTW Primary Energy (kWh/km)	WTW CO_2 Emissions (kg/km)	TCO ($/km)	Fuel Cost ($/km)
Passenger Cars	FCEV	0.528	0.109	0.684	0.083
	BEV	0.223	0.093	0.529	0.024
	PHEV	0.415	0.146	0.454	0.050
	ICEV	0.392	0.132	0.326	0.048
Buses	FCEV	1.401	0.290	2.658	0.220
	BEV	1.587	0.662	1.110	0.170
	PHEV	2.537	0.886	1.515	0.305
	ICEV	4.700	1.586	1.289	0.576
Trucks	FCEV	7.076	1.463	2.037	1.109
	BEV	1.521	0.635	0.648	0.163
	PHEV	2.777	0.937	0.688	0.340
	ICEV	3.610	1.219	0.728	0.442

ASEAN = Association of Southeast Asian Nations, BEV = battery electric vehicle, FCEV = fuel cell electric vehicle, ICEV = internal combustion engine vehicle, PHEV = plug-in hybrid electric vehicle, TCO = total cost of ownership, WTW = well-to-wheel.
Source: Authors.

According to our model's estimation, centralised production, which assumes a 100 km supply chain from production to dispensing, with storage, will incur a higher fuel cost and thus TCO per km. The results of a benchmark scenario with centralised production of hydrogen is presented below in Table 5.4. Since this is only relevant to FCEVs, the results of vehicles with other powertrains remain the same as in Table 5.3. In short, centralised production of hydrogen leads to less primary energy consumption, as well as fewer carbon emissions, from FCEVs due to their higher efficiency compared to forecourt production. However, the cost of hydrogen would be higher, due to the need of transportation, which is costly.

Table 5.4 Benchmark Scenario with Centralised Production of Hydrogen: ASEAN Average Levels

	WTW Primary Energy (kWh/km)	WTW CO_2 Emissions (kg/km)	TCO ($/km)	Fuel Cost ($/km)
FCEV Passenger Car	0.529	0.111	0.690	0.089
FCEV Bus	1.395	0.289	2.673	0.235
FCEV Truck	7.046	1.458	2.115	1.187

ASEAN = Association of Southeast Asian Nations, FCEV = fuel cell electric vehicle, TCO = total cost of ownership, WTW = well-to-wheel.
Source: Authors.

In the sensitivity scenario, hydrogen is predominantly produced from renewables. As Table 5.5 and Table 5.6 show for forecourt production and centralised production of hydrogen, respectively, such will lead to even lower carbon emissions from FCEVs, from a WTW perspective, compared to other powertrains. However, under current technologies of renewable energy, fuel costs for FCEVs will be higher. Again, since the centralised production of hydrogen is only relevant to FCEVs, the results of vehicles with other powertrains remain the same as in Table 5.3.

Table 5.5 Sensitivity Scenario with Forecourt Production of Hydrogen: ASEAN Average Levels

	WTW Primary Energy (kWh/km)	WTW CO_2 Emissions (kg/km)	TCO ($/km)	Fuel Cost ($/km)
FCEV Passenger Car	0.574	0.067	0.702	0.100
FCEV Bus	1.524	0.177	2.703	0.265
FCEV Truck	7.696	0.893	2.264	1.336

ASEAN = Association of Southeast Asian Nations, FCEV = fuel cell electric vehicle, TCO = total cost of ownership, WTW = well-to-wheel.
Source: Authors.

Table 5.6 Sensitivity Scenario with Centralised Production of Hydrogen: ASEAN Average Levels

	WTW Primary Energy (kWh/km)	WTW CO_2 Emissions (kg/km)	TCO ($/km)	Fuel Cost ($/km)
FCEV Passenger Car	0.575	0.068	0.707	0.106
FCEV Bus	1.517	0.176	2.718	0.280
FCEV Truck	7.663	0.891	2.343	1.415

ASEAN = Association of Southeast Asian Nations, FCEV = fuel cell electric vehicle, TCO = total cost of ownership, WTW = well-to-wheel.
Source: Authors.

Based on such results, the following observations are made:

1. The application of FCEVs as passenger cars and buses delivers fewer carbon emissions than vehicles with other powertrains.
2. In the case of FCEV buses, primary energy consumption and fuel cost per km are lower than buses with other powertrains.
3. In all cases, the TCO expressed in dollars per km of FCEVs in all fleets is the highest amongst all types of vehicles. In the case of fuel cell trucks (FCTs), the TCO gap is exceptional. This is mostly due to FCTs still being in the prototype stage, as well as FCT capital costs not being directly available from open sources.
4. If hydrogen is mostly produced from renewable sources, carbon emissions become the lowest amongst all powertrains in the passenger car and bus fleets. In the case of the truck fleet, FCEV carbon emissions are lower than that of the diesel truck. However, such comes at the price of higher fuel cost per km for FCEVs.
5. In the case of FCTs, the relatively low fuel economy, even compared to diesel trucks, is an obvious disadvantage. This may be attributed to fuel economy data of FCTs being rarely disclosed with sufficient details.

4.2. The Future Scenario

Tables 5.7 and 5.8 present the results of the future scenario from our model.

Table 5.7 Future Scenario with Forecourt Production of Hydrogen: ASEAN Average Levels

		WTW Primary Energy (kWh/km)	WTW CO_2 Emissions (kg/km)	TCO ($/km)	Fuel Cost ($/km)
Passenger Cars	FCEV	0.528	0.109	0.376	0.046
	BEV	0.223	0.093	0.531	0.040
	PHEV	0.415	0.146	0.484	0.090
	ICEV	0.392	0.132	0.294	0.090
Buses	FCEV	1.401	0.290	1.426	0.123
	BEV	1.587	0.662	1.184	0.283
	PHEV	2.537	0.886	1.755	0.550
	ICEV	4.700	1.586	1.912	1.208
Trucks	FCEV	7.076	1.463	1.167	0.622
	BEV	1.521	0.635	0.691	0.271
	PHEV	2.777	0.937	0.969	0.621
	ICEV	3.610	1.219	1.114	0.831

ASEAN = Association of Southeast Asian Nations, BEV = battery electric vehicle, FCEV = fuel cell electric vehicle, ICEV = internal combustion engine vehicle, PHEV = plug-in hybrid electric vehicle, TCO = total cost of ownership, WTW = well-to-wheel.
Source: Authors.

Table 5.8 Future Scenario with Centralised Production of Hydrogen: ASEAN Average Levels

	WTW Primary Energy (kWh/km)	WTW CO_2 Emissions (kg/km)	TCO ($/km)	Fuel Cost ($/km)
FCEV Passenger Car	0.529	0.111	0.3789	0.049
FCEV Bus	1.395	0.289	1.433	0.131
FCEV Truck	7.046	1.458	1.064	0.661

ASEAN = Association of Southeast Asian Nations, FCEV = fuel cell electric vehicle, TCO = total cost of ownership, WTW = well-to-wheel.
Source: Authors.

The following observations draw on the future scenario.

1. In the 2030 scenario, with 50% reduction in the capital cost of FCEVs and 50% reduction in the hydrogen fuel costs (including production, transportation, and dispensing), the TCO of FCEVs in terms of dollars per km largely becomes competitive against fossil fuel-powered vehicles, especially in the bus and truck fleets

2. In terms of fuel cost per km, FCEVs also become competitive against fossil fuel-powered vehicles in all three fleets
3. If the capital cost of FCEVs can be cut by 70%, they become the most competitive in terms of both TCO and fuel cost per km in all three fleets

4.3. Country-specific Results

Each ASEAN country has its unique taxes, tariffs, fees and surcharges, as well as incentives and subsidies imposed, on the purchase and use of vehicles. The ASEAN countries also differentiate with their unique power generation mix and thus the costs and emissions of each kWh of electricity. These drive the models' differentiated results. The key observations about each country are summarised in Table 5.9. In each cell, FCEVs' performance or competitiveness is compared to other powertrains in a certain fleet, and ranked, with 1 being the best and 4 being the worst.

Table 5.9 Summary of Key Observations of Each ASEAN Country in the Benchmark Scenario with Forecourt Production

Country	fleet	Energy use / km	CO_2 / km	TCO / km	Fuel cost / km
Brunei Darussalam	Passenger Car	4	1	4	4
	Bus	1	1	4	3
	Truck	4	4	4	4
Cambodia	Passenger Car	4	1	4	4
	Bus	1	1	4	1
	Truck	4	4	4	4
Indonesia	Passenger Car	4	1	4	4
	Bus	1	1	4	3
	Truck	4	4	4	4
Lao PDR	Passenger Car	4	2	4	4
	Bus	1	2	4	2
	Truck	4	4	4	4
Malaysia	Passenger Car	4	1	4	4
	Bus	1	1	4	2
	Truck	4	4	4	4
Myanmar	Passenger Car	4	2	4	4
	Bus	1	1	4	2
	Truck	4	4	4	4
Philippines	Passenger Car	4	2	4	4
	Bus	1	1	4	1

	Truck	4	4	4	4
Singapore	Passenger Car	4	2	4	4
	Bus	1	1	4	2
	Truck	4	4	4	4
Thailand	Passenger Car	4	2	4	4
	Bus	1	1	4	2
	Truck	4	4	4	4
Viet Nam	Passenger Car	4	2	4	4
	Bus	1	1	4	2
	Truck	4	4	4	4

ASEAN = Association of Southeast Asian Nations, Lao PDR = Lao People's Democratic Republic, TCO = total cost of ownership.
Source: Authors.

Table 5.10 presents the results from the future scenario (year 2030), with forecourt production of hydrogen as a comparison to the previous table.

Table 5.10 Summary of Key Observations of Each ASEAN Country in the Future Scenario with Forecourt Production

Country	fleet	Energy use / km	CO_2 / km	TCO / km	Fuel cost / km
Brunei Darussalam	Passenger Car	4	1	3	3
	Bus	1	1	3	2
	Truck	4	4	4	3
Cambodia	Passenger Car	4	1	2	1
	Bus	1	1	3	1
	Truck	4	4	4	4
Indonesia	Passenger Car	4	1	3	2
	Bus	1	1	4	2
	Truck	4	4	4	3
Lao PDR	Passenger Car	4	2	2	2
	Bus	1	2	4	1
	Truck	4	4	4	4
Malaysia	Passenger Car	4	1	3	2
	Bus	1	1	4	1
	Truck	4	4	4	3
Myanmar	Passenger Car	4	2	4	2
	Bus	1	1	4	2
	Truck	4	4	4	3
Philippines	Passenger Car	4	2	2	1
	Bus	1	1	2	1
	Truck	4	4	4	4
Singapore	Passenger Car	4	2	3	2
	Bus	1	1	4	1
	Truck	4	4	4	4
Thailand	Passenger Car	4	2	2	2
	Bus	1	1	2	1
	Truck	4	4	4	4
Viet Nam	Passenger Car	4	2	2	2
	Bus	1	1	3	1
	Truck	4	4	4	3

ASEAN = Association of Southeast Asian Nations, Lao PDR = Lao People's Democratic Republic, TCO = total cost of ownership.
Source: Authors.

5. Key Observations

The following observations draw on the above-reported results and findings:

1. The higher TCO of FCEVs is driven by the very high capital expenditure of the vehicles.
2. FCEVs are also estimated to have higher costs for fuel transportation and dispensing.
3. Hydrogen production pathways are not yet competitive, except for those based on natural gas, coal and biomass.
4. These disadvantages are highly likely to be overturned as continuous R&D brings about technological breakthroughs, combined with the effects of the learning curve and economies of scale, when H_2 supply chains, H_2 transmission and distribution infrastructure and manufacturing of FCEVs come into commercial operation.
5. If renewables-based hydrogen supply chains' GHG benefit is considered, the advantages of H_2 will further boost its competitiveness against other alternative powertrains.
6. Although FCEVs are not yet competitive, the results indicate a future in which FCEVs will become competitive under certain circumstances and in certain application scenarios.
7. Indonesia and the Philippines seem to be closer to bridging the commercial feasibility gaps of FCEVs in the future.
8. FCEV buses will be the most promising application of hydrogen-based powertrains to replace conventional ones.
9. This study has quantified the gaps in both TCO and fuel cost per km, and the policy support in the form of various subsidies, tax incentives and RD&D that can help accelerate the arrival of this future scenario.
10. Pricing emissions will also help bridge the gap in the economic competitiveness of hydrogen-based powertrains to compete with conventional as well as other alternative powertrains.

The availability of high-quality data regarding the technical performances of hydrogen production pathways, hydrogen transportation and storage, hydrogen refuelling stations, and the fuel economy of FCEVs, especially regarding trucks, remain the main limitation of this study. The currently reported results reflect the best available data from the public domain.

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Chapter 6

Conclusion and Policy Recommendations

1. Conclusion

This study consists of following five parts:

a. Review of existing energy polices, especially those pertaining to climate, renewables, and hydrogen, where applicable;

b. Forecast of hydrogen demand potential, including its competitiveness with respect to natural gas and coal for power generation and gasoline and diesel for road and rail transportation;

c. Forecast of hydrogen production potential, including its costs by several technologies, as well as supply costs at a charging station;

d. Well-to-wheel analysis of the economic feasibility and carbon emissions of FCVs using hydrogen;

e. Site visits to the Ministry of Energy or similar offices of selected EAS region countries (data and discussion contents with selected EAS Ministries of Energy include confidential information; as a result, these are only outlined).

The review of energy policies covers ASEAN 7 countries (except Cambodia, Lao PDR, and Myanmar due to their small hydrogen demand and supply potentials), and Australia, China, India, Japan, Republic of Korea, and New Zealand. By reviewing renewables policies, the potential of solar/PV and wind energy is drawn from national power development plans, which is used to forecast the future hydrogen production in chapter 4. The governments of Australia, China, India, Japan, Republic of Korea, and New Zealand have already formulated their hydrogen policies, and Japan and New Zealand are set to draw their hydrogen roadmap.

The scenario approach was applied to forecast EAS countries' hydrogen demand potential in 2040 because of the lack of historical demand data for hydrogen used as energy. Hydrogen basically is used/will be used as transport fuel (vehicles), fuel for power generation, and industrial heat. As a result, we assume three scenarios, applied to these three sectors depending on level of hydrogen penetration. For example, 2%, 10%, and 20% are assumed scenarios for gasoline consumption replaced by hydrogen. For power generation, targeting an additional 20% from 2015, 10%, 20%, and 30% of hydrogen as a mixing rate with natural gas are the assumed scenarios. Scenario 3 represents the highest hydrogen consumption in each sector. As a result, fossil fuel consumption shows a 2% drop from the business-as-usual baseline described by EAS energy outlook prepared by ERIA in 2018 in Scenario 3, with CO_2 emissions also decreasing by 2.7% from the baseline. The impact of the hydrogen demand potential thus looks lower than expected and assumptions of hydrogen penetration could be pessimistic. Deeper study on hydrogen technologies on the demand side should be implemented as a next step.

According to the study on prices, hydrogen for FCVs (US¢30–40/Nm^3 on average) seems to be competitive compared with ordinary gasoline and diesel oil in some parts of the local supply chain, but it will be still higher on average. For hydrogen use for power generation and industry, the prices will be in the government target range, but still will need to improve to get close to the natural gas prices (US$10/mmbtu), even with carbon offset prices (US$41/tonne-$CO_2$) in the case of overseas transportation from Southeast Asia to Japan (around 5,000 km).

There are two types of hydrogen production sources: fossil fuels, such as natural gas and coal (lignite) to apply reforming and gasification technologies, and renewable energy, such as hydro power and solar/PV to apply water electrolysis. Based on the proven fossil fuel reserves and climate data, including solar radiation and wind speed, two hydrogen production scenarios are projected: 'potential' and 'forecast'. The 'potential' scenario refers to technically available production based on the proven reserve and the climate data. The 'forecast' scenario refers to the volume balanced with total forecasted hydrogen demand of the EAS region in 2040, because exporting countries cover the demand of importing countries and intra-regional countries cover their own demand. As a result, a large amount of hydrogen is projected as 'potential' and constitutes more than enough to cover the hydrogen as 'forecast'.

Although the projected production cost by each technology indicates around US¢10–20/Nm^3 in 2040, the hydrogen supply costs at a station, which include transportation costs, will be US¢40–50/Nm^3, as mentioned above. To compete with fossil fuels, further technology development will be expected.

Applying the well-to-wheel analysis, a comparison study focused on total cost (vehicle price, fuel cost, taxes and fees, and other costs related to vehicle operation), fuel consumption, and CO_2 emissions among ICEVs, HEVs, PHEVs, EVs, and FCVs. As a result, the total cost of owning and driving FCVs will be lower than conventional and fossil fuel-powered vehicles by 2030; in the case of bus fleets, this will occur if the capital cost of FCVs can be reduced by 50% compared to current levels. If the decreases in capital cost were to reach 70% in all three fleets, namely passenger cars, buses, and trucks, FCVs would become competitive against conventional vehicles. Depending on the assumptions about the energy and pathway mixes used in producing hydrogen, FCV energy consumption could compete not only with conventional vehicles, but even with EVs, especially in the case of bus fleets. In terms of CO_2, EVs marked lowest, followed by FCVs. This analysis fully depends on assumptions such as those regarding the price data of vehicles, hydrogen supply chains, and transport fuels. Consequently, the price of FCVs will be essential for their competitiveness against other alternative vehicle powertrains from the perspective of total cost analysis.

Regarding the site surveys, we had meetings with hydrogen stakeholders in the following six countries: Australia, India, Indonesia, Malaysia, New Zealand, and Thailand. The meetings consisted of introducing the progress of this study, receiving comments from the stakeholders on its forecasted demand and production potentials, and addressing the countries' hydrogen policies. Australia, New Zealand, Brunei Darussalam, Sarawak state of Malaysia, Japan, Republic of Korea, and China have already started to take actions toward the hydrogen economy, but other countries have only looked at the possibility of hydrogen promoted by developed countries such as Japan.

2. Policy Recommendations

Based on the study results, the following policy recommendations are extracted:

a. Many EAS countries, especially developing ones, currently do not have a clear hydrogen policy. These countries have many energy choices, including fossil fuels, biomass, and renewables such as hydro power and new energy such as solar/PV. In this regard, hydrogen is one of their choices and ERIA should pay attention this point. A comparison study between hydrogen and other energy regarding cost and CO_2 emissions will be implemented for these countries.

b. Hydrogen demand fully depends on its supply costs and prices of FCVs and hydrogen power generation systems. In this study, ERIA applied the scenario approach for penetration of hydrogen demand, but it is recommended that, after deeper research on FCVs and hydrogen power systems with the collaboration of experts, the scenarios be revised.

c. Hydrogen supply costs at stations are forecasted to be US¢40–50/Nm^3, which will be in the range of gasoline prices in some cases, but it is still higher on average than gasoline. The higher price comes from higher supply chain costs, especially hydrogen carrier synthesis (converting hydrogen gas to liquid carrier) and hydrogen regeneration (separating hydrogen gas from liquid carrier). Consequently, deeper study on hydrogen supply chains, including technology research, will be necessary. The technologies of low-cost hydrogen carrier synthesis and hydrogen regeneration might be crucial.

d. Places with high hydrogen demand are usually different from those where it is produced. The study extracted Australia, Brunei Darussalam, Indonesia, Sarawak State of Malaysia, and New Zealand as hydrogen production sites. On the other hand, Japan and Republic of Korea have a large hydrogen demand. Consequently, in order to establish overseas hydrogen supply chains, the following studies are needed: a) standardisation for global trading; b) Investment in shipping and receiving terminals at both sides; and c) seeking for scale merits.

e. With this in mind, a working group to discuss common understandings on hydrogen and standardisation of the supply chain will be set up and meetings will be held regularly. Members of the working group will consist of EAS countries that have interest in developing their hydrogen production and demand potentials.