ERIA Research Project Report 2020, No.04

Brunei Darussalam:
Shifting to a Hydrogen Society

Prepared by

Economic Research Institute for ASEAN and East Asia

Brunei Darussalam: Shifting to a Hydrogen Society

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Preface

Brunei Darussalam has been consuming gasoline and diesel oil for road transport activities due to the increase of personal cars and natural gas for power generation following the rapid increase of electricity demand. In addition, a new refinery, which started its operation at the end of 2019, consumes imported coal for auto generation in the refinery site. According to the country’s energy outlook produced by the Ministry of Energy, the total primary energy supply (TPES), mainly from fossil fuels, will increase significantly at 4.3% per year until 2040 at 5.6% of gross domestic product growth. In parallel, CO_2 emissions will increase at 3.6% annually until 2040.

Whilst variable renewable energy (vRE), such as solar/photovoltaic, is one of the options for Brunei, it will not be a sustainable solution due to its intermittency and lower capacity factor (maximum 15%), the need for a huge land area, and its higher generation cost compared to existing power plants. If the country will shift from internal combustion engine to battery electricity vehicle, it will need additional electricity demand, and power generation to consume natural gas will increase because of insufficient electricity generation by vRE.

Currently hydrogen is highlighted globally. Some East Asia Summit (or ASEAN 10 + 8 countries – Australia, China, India, Japan, Republic of Korea, New Zealand, Russian Federation, and the United States) have formulated their hydrogen strategic plans for future available technology and carbon-free energy. Brunei Darussalam, being a natural gas–rich country has opened a hydrogen demonstration plant in western Brunei Darussalam with the support of Japan. It means that Brunei Darussalam will be a hydrogen production country and will use some portion of the hydrogen to be produced domestically for its internal use, such as road transport sector and power generation. If this could be achieved in the future, gasoline and diesel consumption, as well as natural gas use for power generation, will drastically reduce. The country could also be carbon neutral if it could use hydrogen. But a still-large issue is the much-higher hydrogen supply cost compared to gasoline and natural gas prices.

With these backgrounds, this study forecasts the hydrogen demand potential in Brunei Darussalam by applying the econometrics approach and the hydrogen production potential, especially from natural gas, through technical investigation. In addition, this study touches upon hydrogen supply costs in Brunei Darussalam.

The results of this study are expected to contribute to the wider use of hydrogen not only in Brunei Darussalam but also in the East Asia Summit region.

Professor Hidetoshi Nishimura
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Contents

List of Figures

List of Tables

List of Abbreviations and Acronyms

APS	alternative policy scenario
BAU	business–as–usual scenario
BEV	battery electric vehicle
B$	Brunei dollar
BPC	Berakas Power Company
BRT	bus rapid transit
CCS	carbon capture and storage
CCU	carbon capture and utilisation
CCUS	carbon capture utilisation and storage
CH_2	compressed hydrogen
CO_2	carbon dioxide
DES	Department of Electrical Services
EOR	enhanced oil recovery
ERIA	Economic Research Institute for ASEAN and East Asia
FCV	fuel cell vehicle
FCEV	fuel cell electric vehicle
GHG	greenhouse gas
GT	gas turbine
H_2	hydrogen
IPCC	Intergovernmental Panel on Climate Change
ktoe	kiloton of oil equivalent
kWh	kilowatt-hour
LED	light emitting diode
LNG	liquefied natural gas
LRT	light rail transit
MCH	methylcyclohexane
MMBTu	millions British thermal unit
Mtoe	millions of ton of oil equivalent

MW	megawatt
MWe	megawatt electrical
MWh	megawatt-hour
Nm^3	normal cubic meter
PV	photovoltaic
TFEC	total final energy consumption
TPES	total primary energy supply
US$	United States dollar

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Executive Summary

Brunei Darussalam has started producing hydrogen, called SPERA Hydrogen, from processed gas to be generated during the production process of liquefied natural gas (LNG) and exporting it to Japan from the end of 2019, with the full support of Japan. Hydrogen is basically classified as clean energy because no carbon dioxide (CO_2) is emitted after its combustion. Thus, hydrogen is expected to be used globally in the future.

The country's road transport sector highly consumed gasoline and diesel oil, its share being 38% in 2015, accounting for the highest in the final energy consumption sector. In addition, the major source of power generation in Brunei was natural gas, with a share of 99% in 2015. If the country could shift from oil and gas to hydrogen for transport and electricity generation fuel, it could drastically reduce oil and gas consumption as well as CO_2 emissions. This means that hydrogen could be a sustainable energy or technology for Brunei Darussalam. However, a large issue is hydrogen's high supply cost.

This study forecasts hydrogen demand in Brunei Darussalam until 2040. It targets the road transport and power generation sectors, which are energy intensive. So far, hydrogen has not been used in road transport and power generation. This study applies the scenarios approach: (i) case 1, where 10% of vehicles and gas power plants will be replaced by hydrogen vehicles (fuel cell vehicle or FCV) and gas and hydrogen mixed power plants (hydrogen mixing rate at 10%); (ii) case 2, uses 30%; and (iii) case 3, 50%.

If Brunei will shift to hydrogen, oil consumption in the road sector will decrease by 12% in case 1, 36% in case 2, and 58% in case 3 from oil consumption of business-as-usual (BAU) (no hydrogen use) in 2040. On the other hand, gas consumption in the power generation sector will reduce 1% in case 1, 20% in case 2, and 32% in case 3 under BAU in 2040. As a result, CO_2 emissions will decrease by 3% in case 1, 11% in case 2, and 18% in case 3 compared to BAU. Shifting to hydrogen will also bring economic benefits. The use of hydrogen will lower domestic consumption of oil and gas, and this reduced amount can be exported to Asian countries. If the 2019 oil price will be the same until 2040, the amount will be between US$70 million and US$391 million in all cases, corresponding to 0.5% and 3.0% of gross domestic product in 2018.

Under the hydrogen scenarios in all cases, hydrogen demand is forecasted at 126 ktoe to 714 ktoe. Hydrogen is or will be produced from natural gas through the reforming process, but carbon capture and storage (CCS) will be necessary to shift from grey to blue hydrogen. According to this study, the potential of hydrogen production will be significant, more than 2,500 ktoe in 2040, from both gas reforming and gasification and solar/photovoltaic (PV) (use electricity of solar/PV for electrolysis). This suggests that Brunei Darussalam can shift to a hydrogen society; a remaining issue though is hydrogen's supply cost as it is much higher than current oil and gas prices.

Hydrogen supply cost fully depends on production and transportation technologies and hydrogen production scale. If hydrogen production scale will be large (as in case 3), its cost will surely decline. Also, the production cost of the reforming technology is lower than other hydrogen production technologies. Several transportation technologies bring hydrogen from its production sites to final destinations such as hydrogen charging stations. However, if its transportation scale is large, its cost will surely decline. This study then suggests that if hydrogen demand will be more than 70,000 m^3 per hour, hydrogen supply cost at a refuelling station of 1,000 Nm3/h will decline to around US$0.80/$m^3$. It is much higher than existing gasoline and gas prices, but these prices are fully subsidised by the Brunei government. In addition, considering the two major benefits of hydrogen, which are reduction of CO_2 emissions and savings in oil and gas consumption, the US$0.80/$m^3$ could be acceptable by the Brunei people in the future.

Last but not the least, when Brunei Darussalam shifts to a hydrogen society, its Ministry of Energy should have appropriate hydrogen utilisation policies, action plans, and road map. If necessary, the ministry can obtain various international support such as the pros and cons of hydrogen demand and supply from East Asia Summit countries, like Japan.

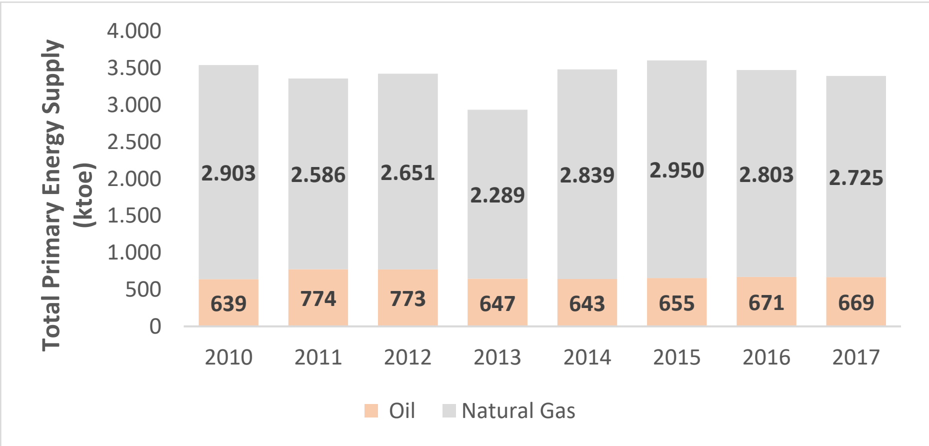
CHAPTER 1

Energy Supply and Demand Situation in Brunei Darussalam

1.1. Total Primary Energy Supply and Total Final Energy Consumption

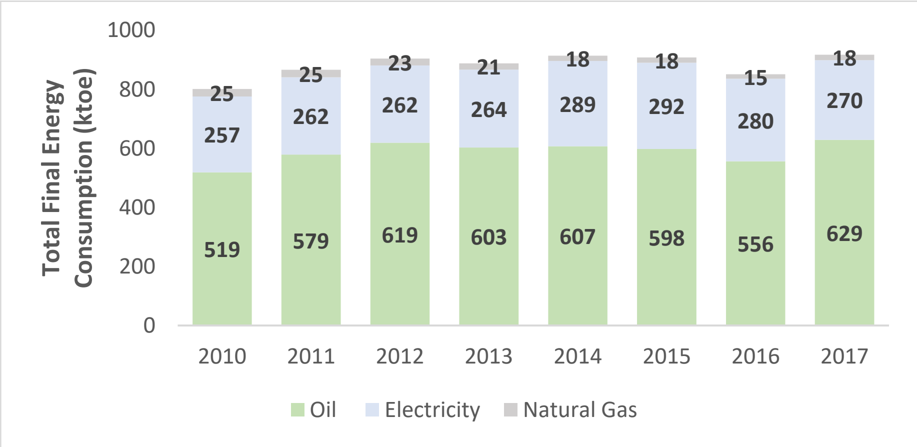
Firstly, we review the historical oil and gas trend of Brunei's total primary energy supply (TPES) and total final energy consumption (TFEC). In particular, oil and natural gas account for 80% and 20% of TPES, respectively. During 2010–2017, oil grew at 0.7% per year but natural gas recorded a negative growth at –0.9% per year due to a decrease in natural gas production (Figure 1.1). Over the same period, the TFEC expanded at 2% per annum; however, oil consumption grew at a faster rate, at 2.8%, higher than the TFEC. Consumption from natural gas was reduced at 4.6% per annum, whilst electricity consumption recorded a growth of 0.7% per year (Figure 1.2).

Figure 1.1: Total Primary Energy Supply, by Fuel Type, in Brunei Darussalam



Source: APEC Energy Working Group (2020).

Figure1.2: Total Final Energy Consumption, by Fuel Type, in Brunei Darussalam



Source: Author (2020).

1.2. Energy Security

Brunei relies heavily on fossil fuels for its domestic power generation (natural gas and diesel) and road transport (gasoline and diesel). Although domestic supplies certainly remained secure, the vulnerability of these supplies would entail disruptions that could cause power outages and insufficient fuel supply. Therefore, it is important to increase the reliability of these supplies to lessen the country's vulnerability and the economic risks associated with interrupted power and fuel shortages.

1.3. Environment and Climate Change

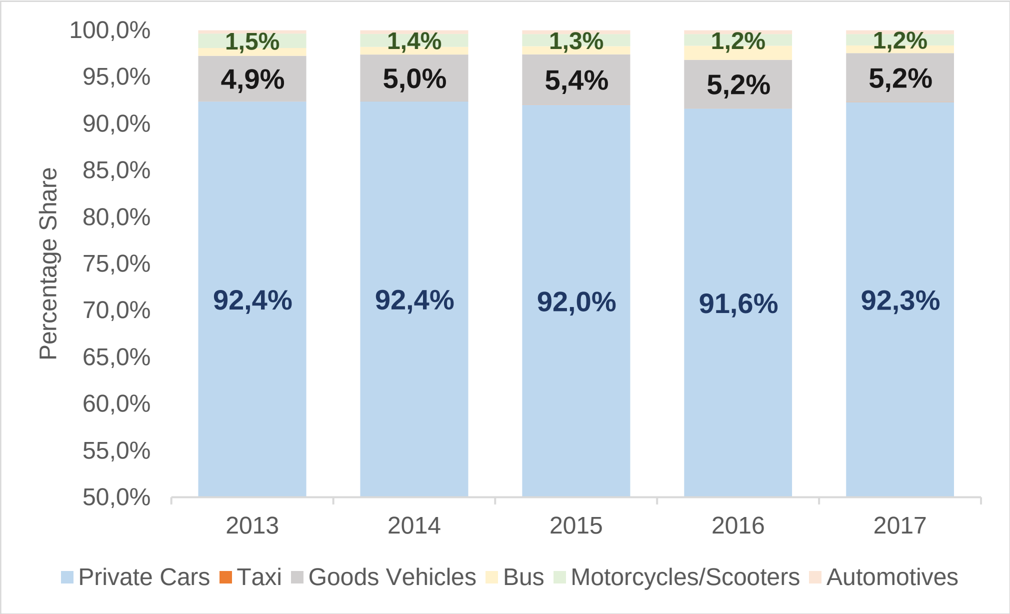
Brunei is one of the countries with the lowest emissions of carbon dioxide (CO_2). Despite being negligible, emissions are projected to grow significantly as the economy grows in the next few years. Hence, being a signatory to the Paris Agreement, the country is committed to reduce its total emissions by 2035, via:

- Energy sector – reduction of total energy consumption by 63%;
- Land transport sector – reduction of CO_2 emissions from morning-peak-hour vehicle use by 40%; and
- Forestry sector – increase in total gazette forest reserve area from 41% to 55%.

1.4. Current Road Transport Profile

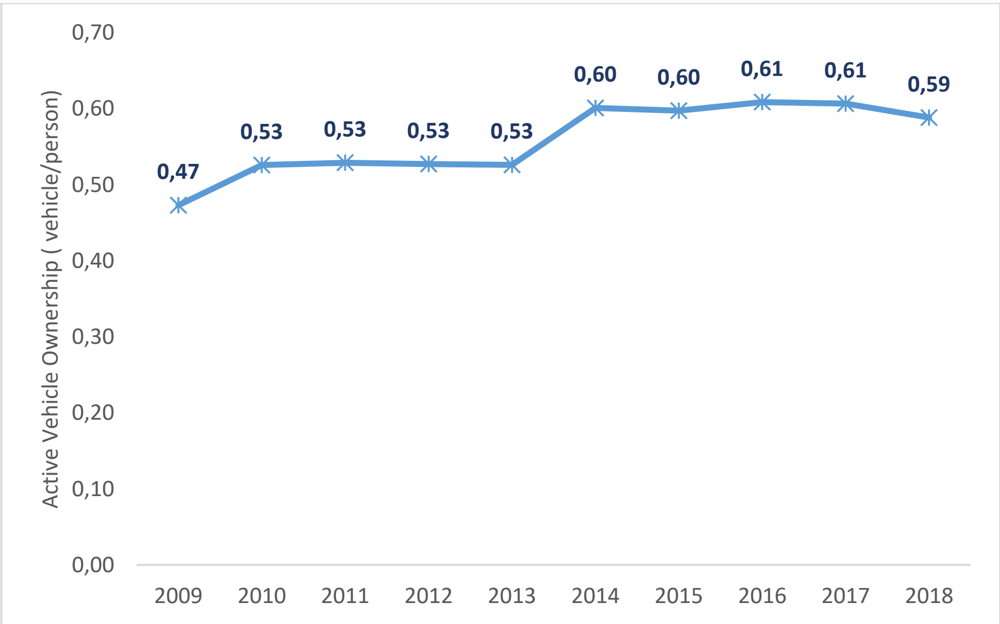
Road transport accounts for about half of the country's final energy consumption. Private vehicles constitute more than 90% of the total fleet, whilst other vehicle types account for the remaining 10% (Figure 1.3). Gasoline and diesel vehicles are dominant, accounting for about 78% and 21%, respectively. Statistics show that there were about 282,345 active vehicles for a population of 442,400 in 2018, equivalent to a vehicle ownership of about 0.59 active vehicles per person (Figure 1.4).

Figure 1.43: Share of Active Vehicles in Brunei Darussalam



Source: Ministry of Finance and Economy (2019).

Figure 1.4: Active Vehicle Ownership in Brunei Darussalam

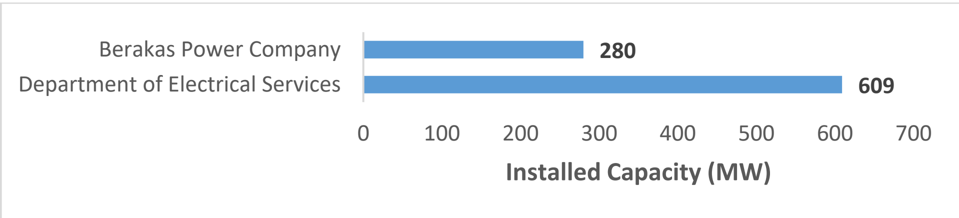


Source: Author (2019).

1.5. Current Power Sector Profile

About 98% of the electricity supplied in Brunei comes from natural gas, with a remaining 1% collectively coming from diesel and solar PV. The Department of Electrical Services (DES) – which owns four natural gas power stations (Gadong 1A, Gadong 2, Bukit Panggal, and Lumut) and a diesel power station (Belingus) – supplies about 58% of the national electricity requirements covering mainly residential areas. The Berakas Power Company (BPC) – which operates three main natural gas power stations (Berakas, Gadong 3, and Jerudong) – supplies the remaining 42% that covers most of the strategic and critical areas such as government offices, hospitals, an international airport, etc. In addition, the BPC recently installed OREgen™[1] waste heat recovery system at its Berakas station that recovers waste heat from gas turbines and converts it into 14 MW of extra net electricity without using fuel or water and does not produce additional emissions. The existing total capacity for public electricity generation stands at 889 MW, out of which 609 MW and 280 MW come from DES and BPC, respectively (Figure 1.5).

Figure 1.5: Installed Capacity of National Utilities in Brunei Darussalam



Source: Author (2020).

Most natural gas power plants in Brunei Darussalam in both DES and BPC systems have turbine models originating from General Electric. DES turbines are of types frame 5 and frame 6B, whilst aeroderivative LM2500 turbines make up the BPC system (Table 1.1).

[1] OREgen™ is a thermodynamic superheat cycle that recovers waste heat from gas turbine exhaust and converts it into electric energy The thermodynamic cycle is the traditional Rankine cycle, using an organic fluid as working fluid. Heat from the turbine exhaust is transferred to a closed diathermic oil loop, which acts as thermal vector and is used to heat an organic fluid loop. This lower temperature heat is then converted into useful work that generates power.

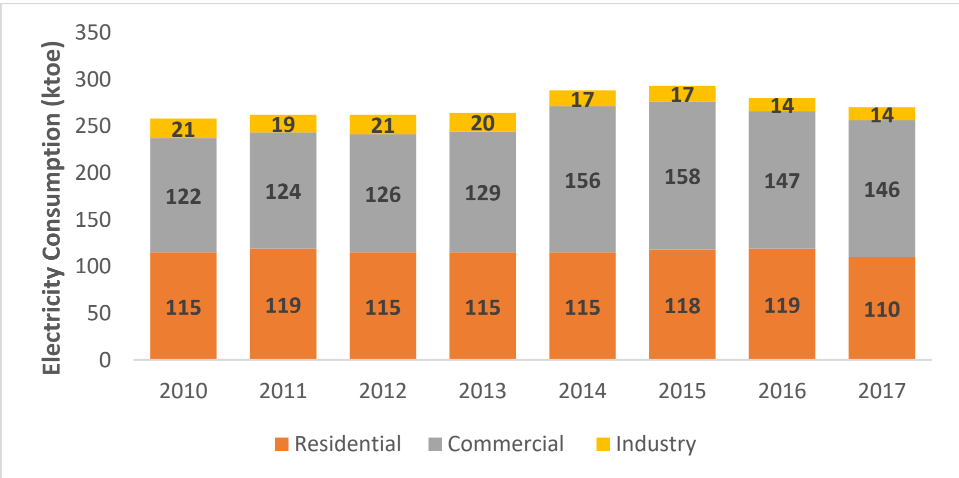
Table 1.1: Gas Turbine Models of DES and BPC Systems

Power Station	Gas Turbine Model
Department of Electrical Services (DES)	
Gadong 1A	GE Frame 6B
Gadong 2	GE Frame 6B
Bukit Panggal	GE Frame 6B
Lumut	GE Frame 5
Berakas Power Company (BPC)	
Berakas	GE LM2500
Gadong 3	GE LM2500
Jerudong	GE LM2500

Source: Power Systems Consultants Asia Pte. Ltd. (2016).

Figure 1.6 shows the electricity consumption across the three main demand sectors in Brunei. Between 2010 and 2017, total electricity demand grew at 0.7% per year, from 258 ktoe to 270 ktoe. The commercial sector constitutes the largest share in electricity consumption that increased from 122 ktoe to 146 ktoe, corresponding to an annual growth of 2.6%. This is followed by the residential sector at 43% share, despite registering a negative annual growth at –0.6%.

Figure 1.6: Electricity Consumption across Demand Sectors in Brunei Darussalam



Source: APEC Energy Working Group (2020).

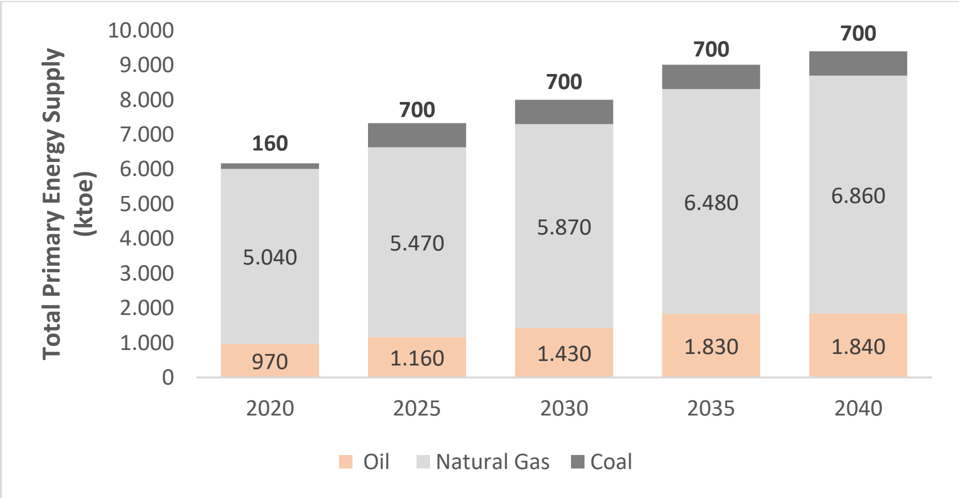
CHAPTER 2

Energy Outlook of Brunei Darussalam

2.1. Total Primary Energy Supply

Under the business–as–usual scenario (BAU), total primary energy supply (TPES) is anticipated to reach 9,390 ktoe by 2040. Natural gas will remain the dominant source of energy supply, accounting for about 73%. This is followed by oil at 20%, and coal at 7%. Coal is expected to provide energy for the new large petrochemical complex in Pulau Muara Besar (Figure 2.1). Brunei Darussalam will continue to become a net energy exporter in the future (ERIA, 2019).

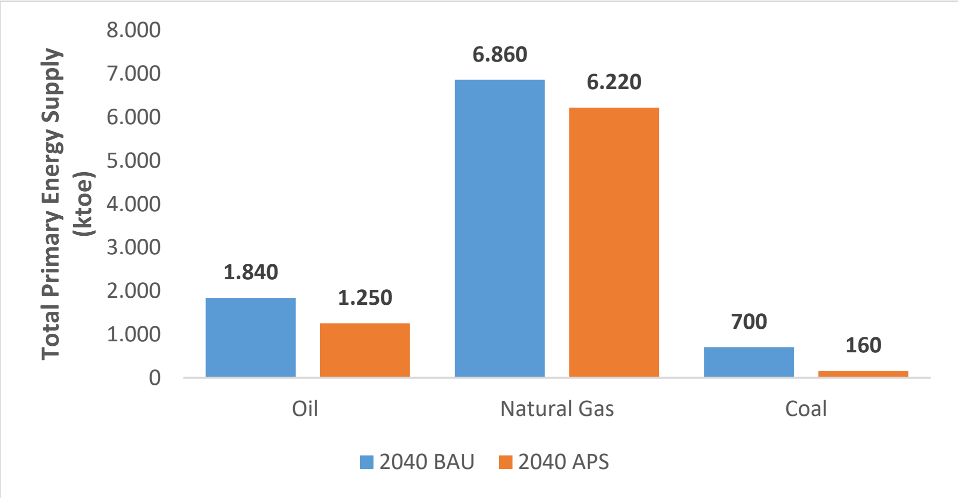
Figure 2.1:Total Primary Energy Supply, by Fuel Type, under BAU (2020–2040)



Source: ERIA (2019).

With the promotion of energy efficiency and conservation and renewable energy supply under the alternative policy scenario (APS), particularly from solar and waste-to-energy sources, alternatively, oil and natural gas will significantly drop in their TPESs against their BAU supplies. Oil supply is expected to decrease by 32.1%, whilst natural gas is expected to drop by 9.3%, and coal by 77.1% (Figure 2.2) (ERIA, 2019).

Figure 2.2: Comparison of TPES between BAU and APS (2040)

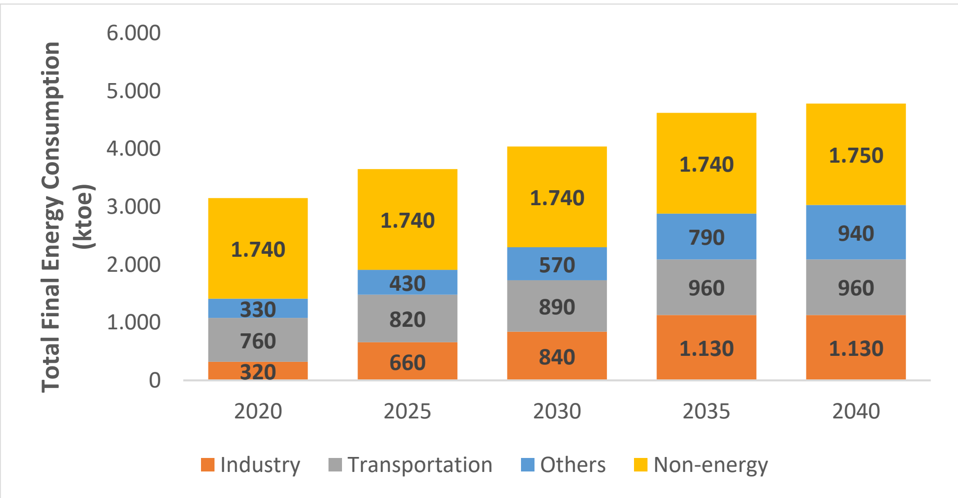


APS = alternative policy scenario, BAU = business-as-usual scenario,
TPES = total primary energy supply.
Source: ERIA (2019).

2.2. Total Final Energy Consumption

Total final energy consumption (TFEC) is projected to increase at 2.1% per year during 2020–2040 to 4,780 ktoe under BAU by 2040, with non-energy use being dominant at 37% share. The large increase of non-energy use, from 20 ktoe in 2015 to 1,740 ktoe in 2020, is due to the upcoming large fertiliser plant expected to operate in 2021. The industry sector's consumption will experience the highest growth rate, at 6.5% per year, followed by others (residential and commercial sectors) at 5.4%, and transport at 1.2% (ERIA, 2019) (Figure 2.3).

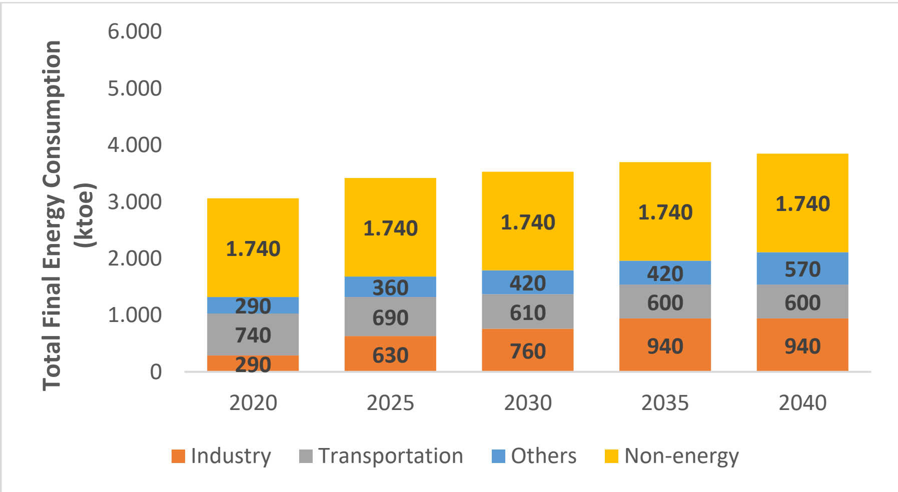
Figure 2.3: Total Final Energy Consumption, by Sector, under BAU (2020–2040)



BAU = business-as-usual scenario.
Source: ERIA (2019).

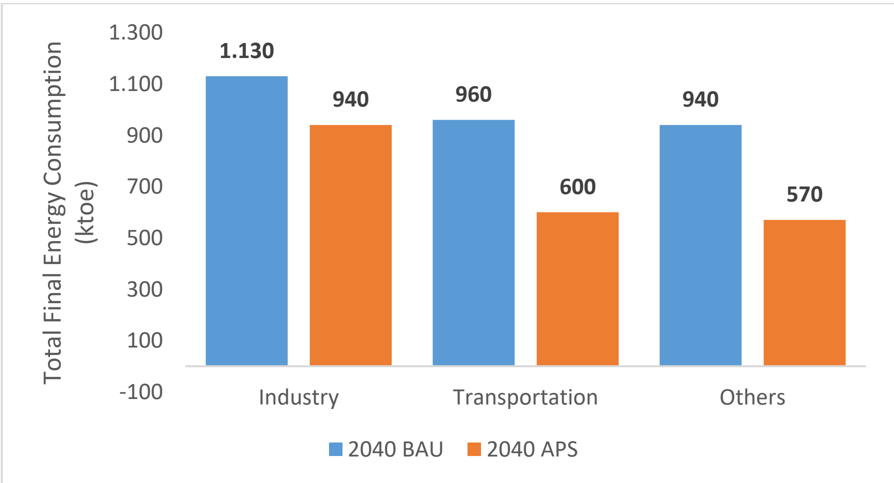
Under the APS, TFEC is expected to reach 3,850 ktoe by 2040 (Figure 2.4), which is a reduction of 19.5% from its BAU value. Both transport sector and others (residential and commercial sectors) are expected to have the biggest reduction in their BAU values, 39.4% and 37.5%, respectively (Figure 2.4). For transportation, this stems from the improvement in vehicle fuel efficiency in the future due to proposed fuel economy regulations. For the residential and commercial sectors, implementation of building guidelines on energy efficiency and conservation as well as standards and labelling scheme would be the main factors in TFEC reduction.

Figure 2.4: Total Final Energy Consumption, by Sector, under APS (2020–2040)



APS = alternative policy scenario.
Source: ERIA (2019).

Figure 2.5: Comparison of TFEC between BAU and APS (2040)



APS = alternative policy scenario, BAU = business-as-usual scenario,
TFEC = total final energy consumption.
Source: ERIA (2019).

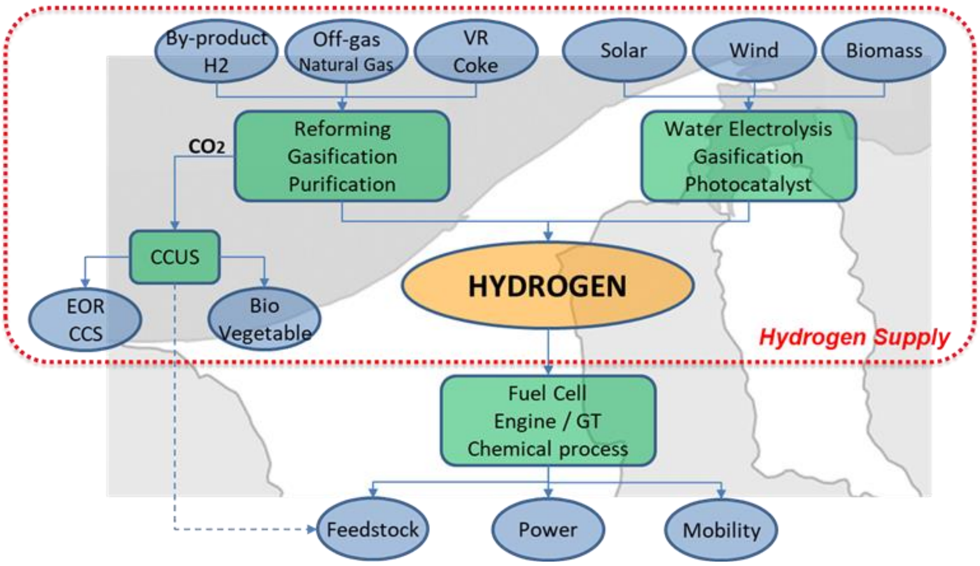
CHAPTER 3

Potential of Hydrogen Production

3.1 Hydrogen Production Resources

Hydrogen can be produced potentially from a broad range of resources including fossil fuels such as by-product hydrogen, natural gas, vacuum residue and coke, and renewable energies such as solar, biomass, and wind energy, and others. The commonly known major hydrogen sources are shown in Figure 3.1.

Figure3.1: Hydrogen Supply and Demand Model in Brunei Darussalam



CCS = carbon capture and storage, CCUS = carbon capture utilisation and storage, CO_2 = carbon dioxide, EOR = enhanced oil recovery, GT = gas turbine, H_2 = hydrogen, VR = vacuum residue.
Source: Author (2020).

For the fossil fuel–derived hydrogen, three production methods are listed: (i) by-product hydrogen utilising purification technologies such as pressure swing adsorption; (ii) reformed hydrogen from flaring gas, reinjection gas, and natural gas of mid-small gas fields using gas reforming technology; and (iii) gasified hydrogen of liquid (vacuum residue, pitch) and solid (coke, coal, lignite) using gasification technology.

In addition to the production technologies, it is important to consider how to effectively manage carbon dioxide (CO_2) produced during hydrogen production processes for fossil fuel–derived hydrogen. CO_2 can be captured and utilised for enhanced oil recovery (EOR), feedstock for chemical products, or stored underground.

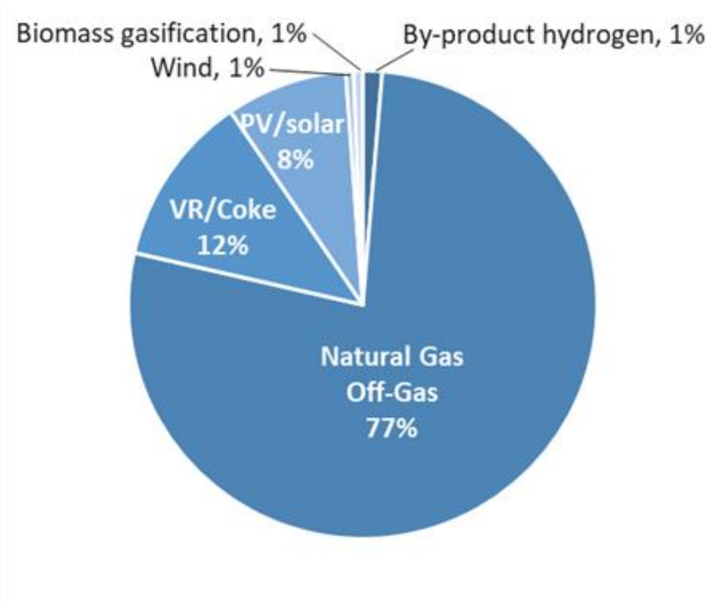
On renewable energy–derived hydrogen, renewable electricity such as solar, wind, hydro, and geothermal can be converted into hydrogen through water electrolysis technology, and biomass can produce hydrogen by using gasification technology.

In the future, new technologies such as biotechnology and photocatalyst technology may pave the way to diversify and increase the options in producing hydrogen from renewable energy.

3.2 Potential of Hydrogen Production

Brunei has a hydrogen production potential of 2.75 Mtoe, with natural gas reforming accounting for 77% of the total, followed by gasified hydrogen from vacuum residue/coke. In renewable resources, solar/photovoltaic (PV) will be a major supply source, accounting for 8% of the total (Figure 3.2).

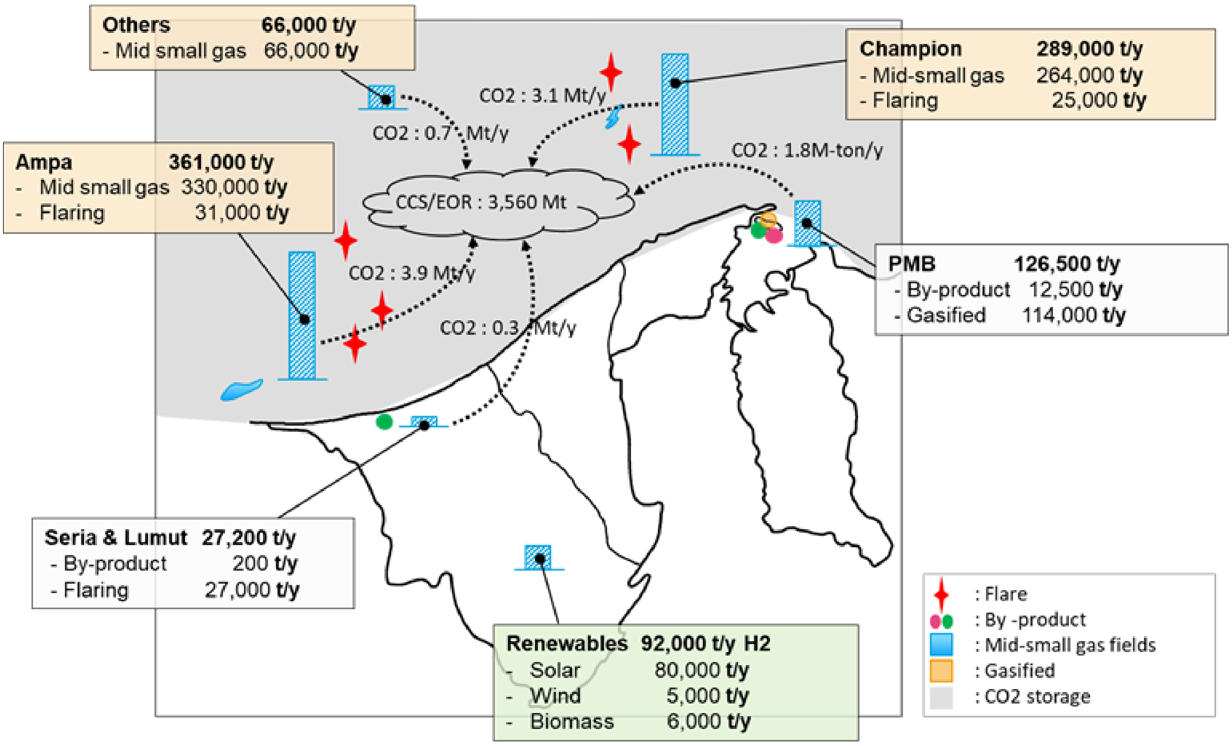
Figure 3.2: Hydrogen Production Potential, by Source



PV = photovoltaic, VR = vacuum residue.
Source: Author (2020).

Figure 3.3 shows that, regionally, nearly 80% of production potential comes from offshore natural gas reserve, and Pulau Muara Besar and Seria & Lumut follow it.

Figure 3.3: Hydrogen Production Resources in Brunei Darussalam

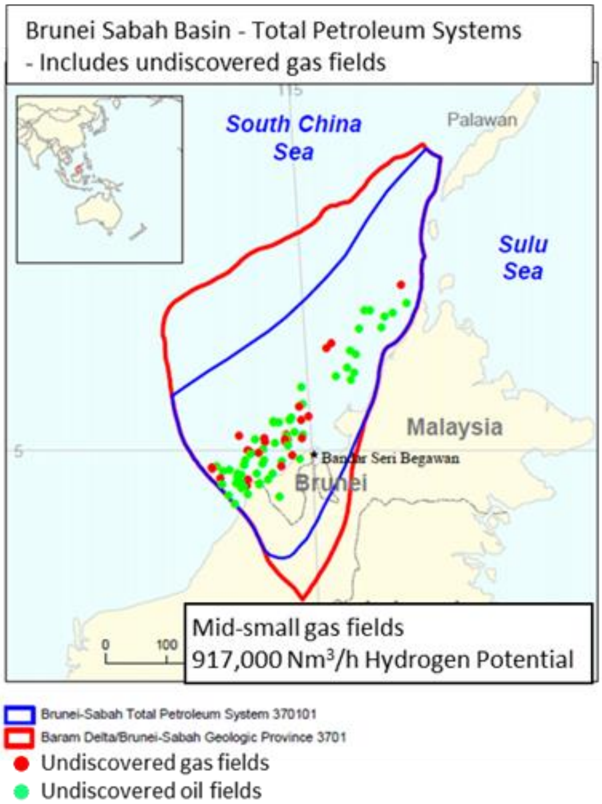


CCS = carbon capture and storage, EOR = enhanced oil recovery, T = tonne.
Source: Author (2020).

3.2.1. Potential of producing hydrogen from natural gas

Thanks to the presence of its large amount of natural gas reserves, Brunei has a relatively large hydrogen production potential from natural gas reforming derived from flaring gas and natural gas of mid-small gas fields compared to other resources. The total potential of hydrogen production from natural gas reaches around 2.12 Mtoe, nearly 90% of which comes from mid-small gas fields (Figure 3.4).

Figure 3.4: Hydrogen Production Resources from Mid-small Gas Fields

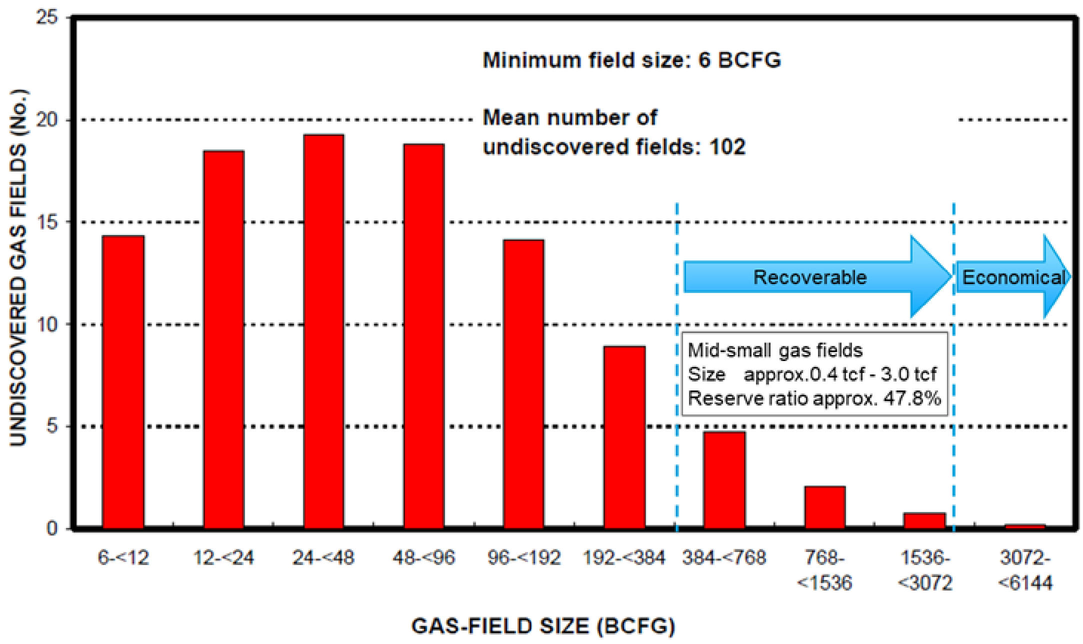


Source: USGS (2000).

Brunei Darussalam reportedly has natural gas reserves of 9.5 trillion cubic feet as of 2017 (BP, 2018). However, normally in the natural gas industry, gas fields of over 0.5 trillion cubic feet are considered recoverable and those over 5 trillion cubic feet are economical in the conventional natural gas development activity (JOGMEC, 2018). From the graph of the US Geological Survey (Figure 3.5), gas reserves of 0.4–3.0 trillion cubic feet, which are considered recoverable and uneconomical in natural gas development, will share around 48% of the total reserves in Brunei. Considering all these, the potential of producing hydrogen from mid-small gas fields could reach around 1.89 Mtoe in the country.

As the targeted mid-small gas fields are uneconomical in large-scale natural gas development, it will not affect the country’s liquefied natural gas (LNG) business.

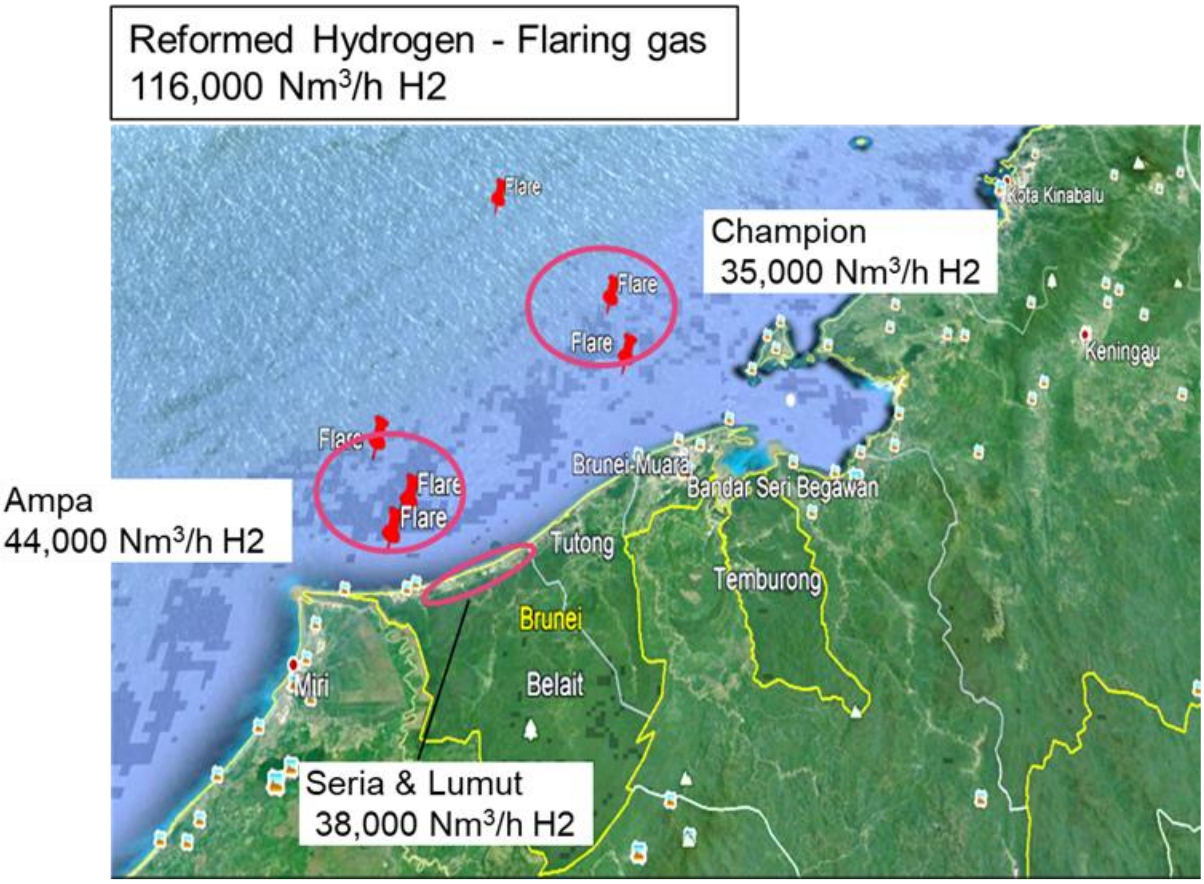
Figure 3.5: Brunei–Sabah Basin Undiscovered Gas Fields



BCFG = billion cubic feet of gas.
Source: USGS (2000).

The other potential in producing hydrogen from natural gas comes from gas flaring from already-developed gas fields. The National Oceanic and Atmospheric Administration (NOAA) observed around 0.3 billion cubic meters of gas flaring around Brunei Darussalam in 2016 (NOAA, 2019), with offshore accounting almost 70% of the total. Figure 3.6 shows the hydrogen production potential distribution estimated from gas flaring activity, and the gas reserve distribution around Brunei Darussalam.

Figure 3.6: Hydrogen Production Resources from Gas Flaring



Note: Upstream hydrogen production rates by region were estimated based on the natural gas reserve ratio.
Source: NOAA (2019).

As the gas reserves are relatively concentrated in offshore areas, the hydrogen production potential in offshore areas accounts for around 70% of the total potential from flaring gas.

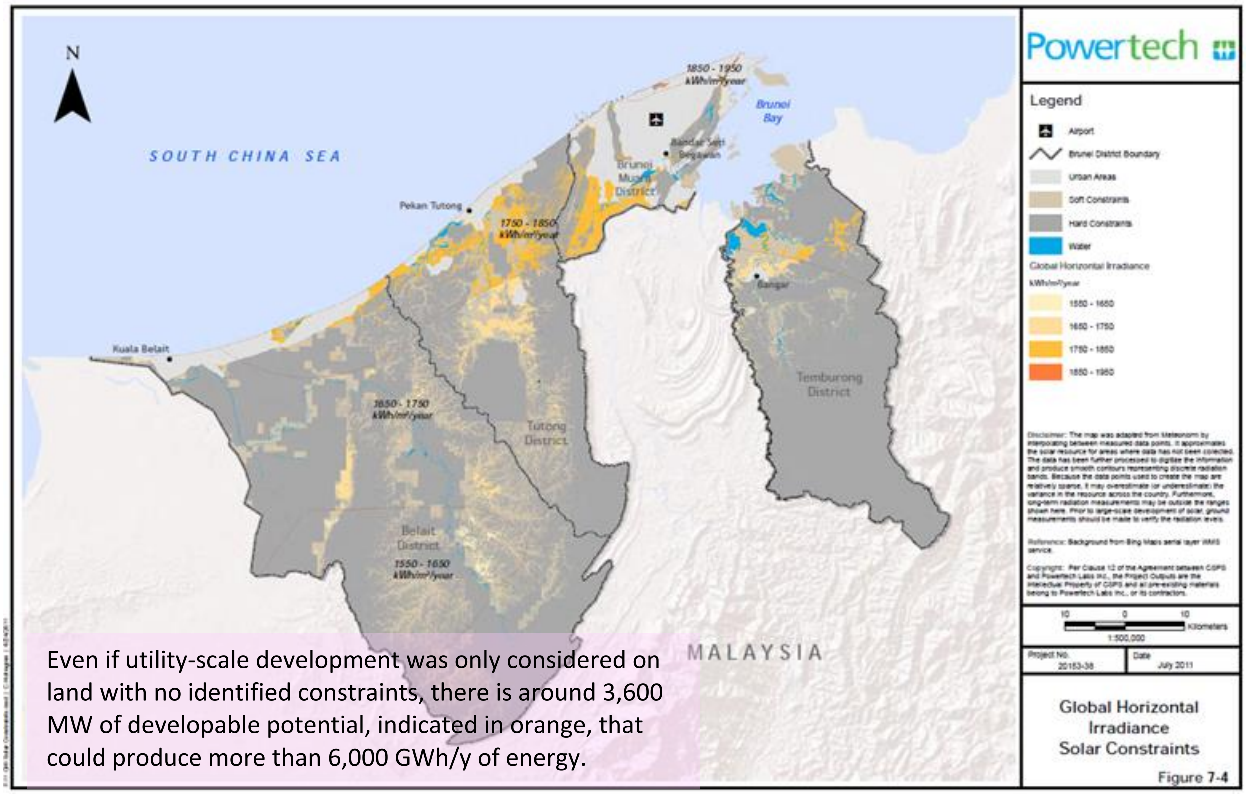
3.2.2. Potential of producing hydrogen from renewable energy

Brunei has a renewable energy–derived hydrogen production potential of 0.27 Mtoe, and solar PV–derived hydrogen shares 87% of it. In spite of abundant solar irradiation across the country, due to constraints on national land and natural reserve area, the hydrogen production potential from solar PV is relatively limited compared to that of neighbouring countries.

The country reportedly has developable a solar power generation potential of 3,600 MWe excluding offshore and considering only onshore with no identified constraints, as indicated in orange (Figure 3.7) (Powertech, 2011). Considering the Wawasan Brunei 2035 (Ministry of Energy, 2014) renewable energy target of 954,000 MWh by 2035, which corresponds to around 600 MWe (calculated using capacity factor of 0.17, the Asian average), the remaining solar power potential that could be used to produce green hydrogen would be around 3,000

MW. Calculating the hydrogen production potential from these data, such potential derived from solar PV would be around 0.23 Mtoe.

Figure 3.7: Hydrogen Production Potential of Solar Energy in Brunei Darussalam



Source: Powertech (2011).

3.3. Hydrogen Production and Transport Cost

3.3.1. Hydrogen production cost

a. Key assumptions

Brunei Darussalam's major hydrogen sources are natural gas (flare gas, mid-small gas), pet coke, biomass, and solar.

To calculate the costs of hydrogen production from each source of hydrogen with each hydrogen production method, key assumptions are set and shown in Table 3.1.

Table 3.1: Key Assumptions of Each Hydrogen Production Method

Source	Process	Key Assumptions	Data Source
Flare gas Mid-small gas field	Steam reforming	• Investment cost: ○ 2017: US$2,000 per Nm^3/hour; and ○ 2040: US$1,650 per Nm^3/hour • Efficiency: ○ 2017: 64%; and ○ 2040: 83%	IAE report
Petroleum coke	Gasification	• Investment cost: ○ 2017: US$10,000 per Nm^3/hour; and ○ 2040: US$8,890 per Nm^3/hour • Efficiency: ○ 2017: 42%; and ○ 2040: 53%	In-house data
H_2 production using fossil fuel	Carbon capture and storage (CCS)	• CO_2 cost: ○ 2015: US$70.00 per tonne; ○ 2040: US$48.00 per tonne	CCSU Singapore Perspectives
Biomass	Gasification	• Investment cost: ○ 2017: US$5,220 per Nm^3/hour; and ○ 2040: US$4,700 per Nm^3/hour Efficiency: ○ 2017: 44%; and ○ 2040: 50%	In-house data
Solar	Electrolysis	• Investment cost: ○ 2017: US$5,940 per Nm^3/hour; and ○ 2040: US$2,950 per Nm^3/hour Efficiency: ○ 2017: 79%; and ○ 2040: 82%	IAE report IEEJ report

CCSU = carbon capture, storage and utilisation, IAE = The Institute of Applied Energy, IEEJ = Institute of Energy Economics, Japan.
Source: Author (2020).

Hydrogen production will strongly depend on energy price of feedstock and process efficiency. The feedstock prices of each hydrogen production process for the three scenarios are presented in Table 3.2.

Table 3.2: Feedstock Prices Applied to Evaluate Hydrogen Cost for Each Production Process

H_2 Production Process	Feedstock	Unit	Scenario		
			Current	2040	Best
Steam reforming with carbon capture and storage (CCS)	Natural gas	US$/ MMBTu	3.4	5.7	5.7
Petroleum coke gasification	Petroleum coke	US$/tonne	82.7	101.7	101.7
Biomass gasification	Wood	US$/tonne	100	100	100
Alkaline electrolyser/fluctuating power	Electricity	Cents per kWh	8.0	2.5	N/A

kWh = kilowatt-hour, MMBTu = millions British thermal unit.
Source: Author (2020).

The costs of each production process are estimated in the current scenario, the 2040 scenario, and the best (new tech or future tech) scenario.

Production from fossil fuel sources also requires adding the cost of carbon capture utilisation and storage (CCUS).

These assumptions for capacity factor, CCS cost, and CO_2 value utilised in the calculation of hydrogen production costs are shown in Table 3.3. Capacity factor for alkaline electrolyser/fluctuating power is set as 20% based on solar power that is a major renewable energy source in Brunei.

Table 3.3: Assumptions for Capacity Factor and CCS Costs

H_2 Production Process	Capacity Factor (%)	CCS Cost Current (US$ per tonne of CO_2)	CCS cost 2040 (US$ per tonne of CO_2)	CCS Value Best (US$ per tonne of CO_2)
Steam reforming with CCS	91	70	48	20
Petroleum coke gasification	91	70	48	20
Biomass gasification	85	NA	NA	20
Alkaline electrolyser/fluctuating power	20	NA	NA	NA

CCS = carbon capture and storage.
Source: Author (2020).

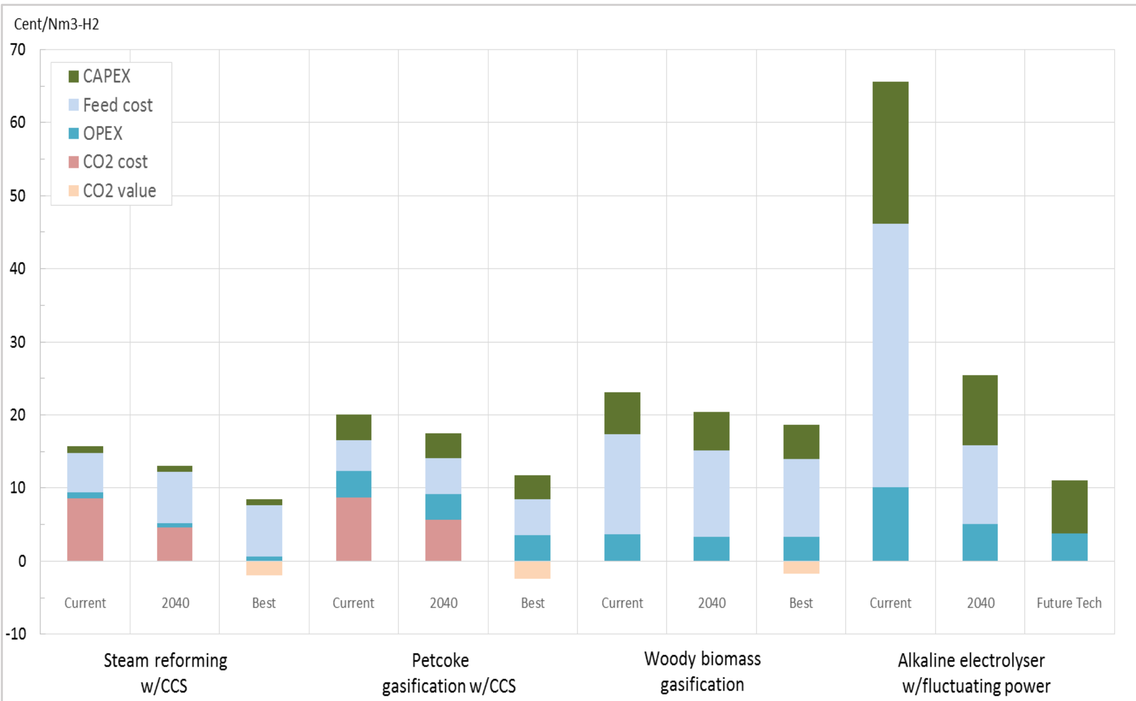
b. An example of hydrogen production cost

Figure 3.8 illustrates an example of hydrogen production cost for each of the above production processes. The cost evaluation is based on various references specific to the processes:

- Biomass gasification is based on literature from Ooiwa (2014) and the Forestry and Forest Products Research Institute (2017).
- Electrolysis is based on literature from Fujimoto (2018) and Sayama and Miseki (2014).
- Supply chain is based on literature from Ishii and Maruta (2018) and Yamamoto (2018).
- CCS cost is based on literature from Karimi and Shamsuzzaman (2014).
- H2 from renewable energy is based on literature from Kato (2016).
- Fuel cell is based on literature from Korner (2015).

The hydrogen production cost in 2040, ranked from low to high, is in the order of 'Steam reforming with CCS', 'Petcoke gasification with CCS', 'Woody biomass gasification', and 'Water electrolysis with fluctuating power'.

Figure 3.8: Example of Hydrogen Production Costs, by Each Process

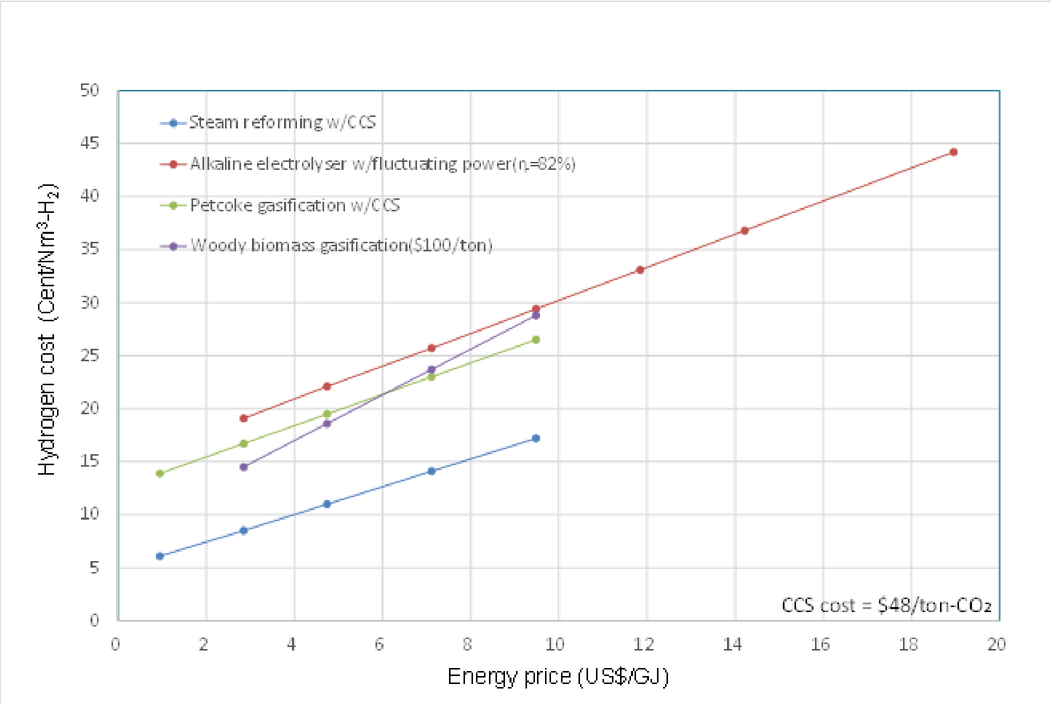


CCS = carbon capture and storage.
Source: Author (2020).

c.	Sensitivity to feedstock price

In the case of hydrogen production from fossil fuels, the production cost will be relatively sensitive to feedstock price and CO_2 management cost. Figure 3.9 shows an example of how the feedstock price (expressed in energy price) will influence the production cost in 2040.

Figure 3.9: Hydrogen Production Cost to Feedstock Price



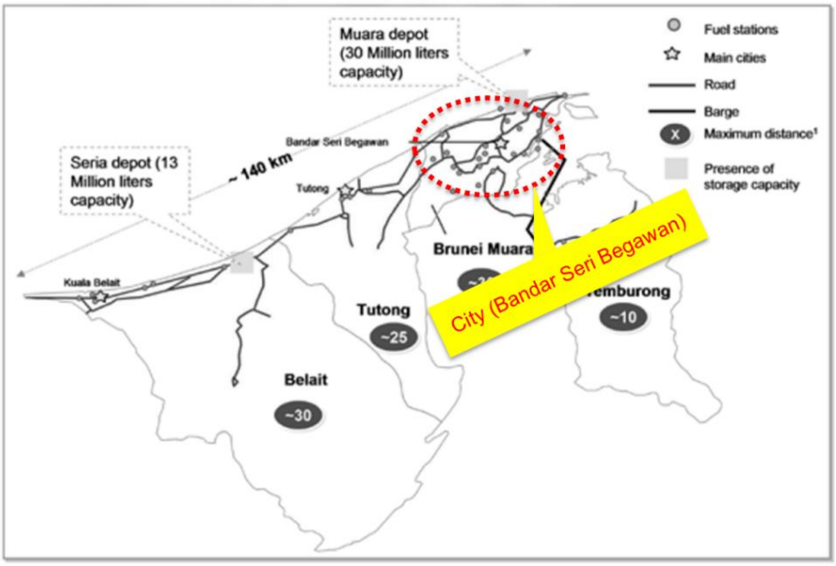
CCS = carbon capture and storage.
Source: Author (2020).

*3.3.2.	Hydrogen transportation cost*

a.	Transportation circumstances of Brunei Darussalam

Figure 3.10 shows that the maximum transport distance is less than 200 km from Kuala Belait (west end) to Temburong (east end). Brunei’s population and energy and fuel requirements are concentrated in Bandar Seri Begawan, the capital city. Therefore, the maximum distance from the domestic hydrogen production site to the domestic hydrogen demand site will be 200 km.

Figure 3.10: Transportation Distance in Brunei Darussalam



Source: Ministry of Energy (2014).

To evaluate fuel prices for mobility, the existing fuel prices listed in Figure 3.11 will be the benchmark. Fuel prices in Brunei are inexpensive and have never been changed due to the country's subsidy policy since 2008. During Energy Day in Brunei Darussalam in May 2010, the government completely lifted the subsidy only for that day and offered only fuels at market prices. This initiative was designed to remind the consumers of actual fuel prices and to make them aware of the cost of the subsidies.

Figure 3.11: Existing Fuel Prices in Brunei Darussalam

Brunei Darussalam's Commercial Fuel Price
(Unsubsidised Price)
On Brunei's Energy day 24 May 2010, Monday

Fuel Grade	Commercial Price (B$/litre) 24 May 2010 ONLY	Subsidised Price (B$/litre)
Premium 97	0.98	0.53
Super 92	0.92	0.519
Regular 85	0.86	0.36
Diesel	0.91	0.31

- Quite Inexpensive Gasoline Price B$ 0.53/L for Premium 97)
- Large Government Financial Burden (B$ 180 – 400 million per annum)
- No. 1 Car Ownership Ratio (691 cars/1,000 people in 2012)

Source: Borneo Bulletin/Bru–Direct (2010).

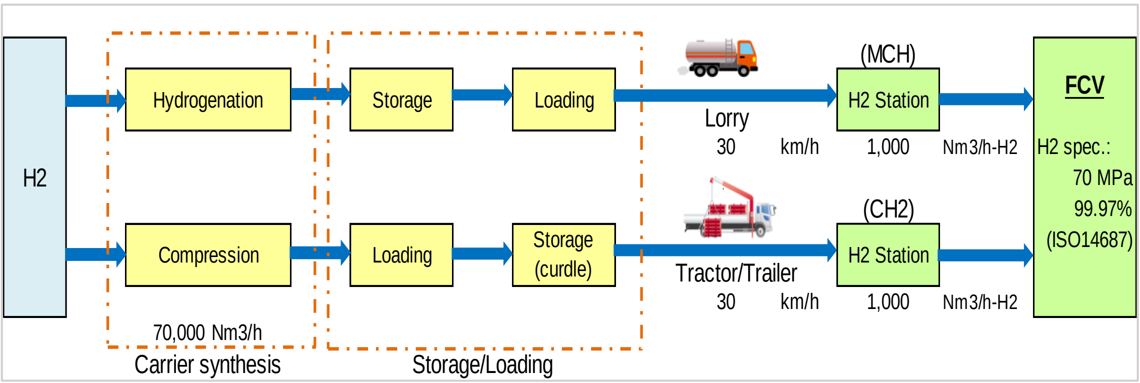
b. Comparison of transport costs between liquid organic chemical hydride and compressed hydrogen

The study includes two hydrogen transportation pathways, liquid organic chemical hydride (MCH) and compressed hydrogen (CH_2).

The transportation model for the two pathways, using trucks to transport hydrogen, are shown in Figure 3.12. As a representative case, the feedstock is natural gas (flare gas, mid-small gas) by using steam reforming process, and the hydrogen capacity for carrier synthesis process and hydrogen refuelling station is 70,000 Nm^3/hour and 300 Nm^3/hour or 1,000 Nm^3/hour, respectively. The hydrogen capacity of carrier synthesis process nearly satisfies the hydrogen demand of 175,000 fuel cell vehicles (FCVs). The number of FCVs corresponds to half of the private vehicles in Brunei in 2040.

In general, the CH_2 transportation pathway is more economical for shorter transport distance and smaller volume compare with that of the MCH.

Figure 3.12: Transportation Model of MCH and CH_2 (1,000 Nm^3/h-H_2)

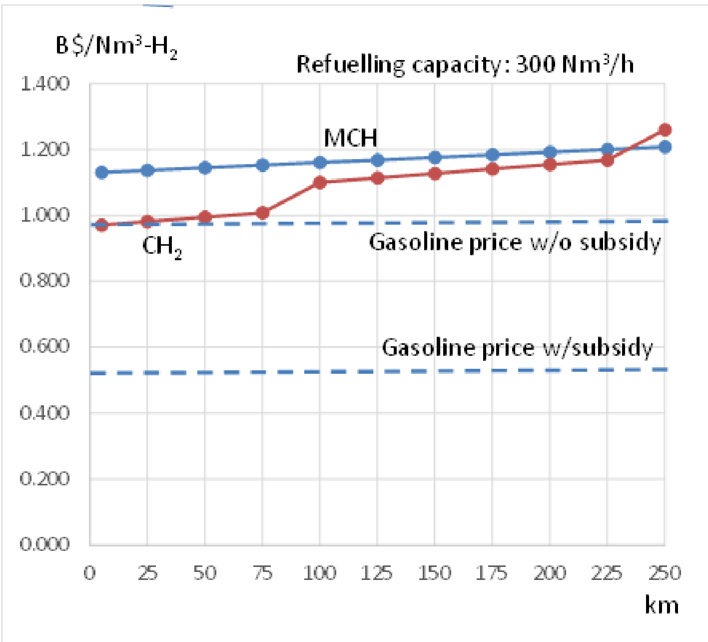


CH_2 = compressed hydrogen, FCV = fuel cell vehicle, MCH = methylcyclohexane.
Source: Author (2020).

Cost comparison results between MCH and CH_2 are illustrated in Figures 3.13 and 3.14. The difference between the two figures is in the refuelling capacity, the former is 300 Nm^3/h and the latter, 1,000 Nm^3/h, respectively. In this calculation, the feed H_2 cost is derived from the cost of hydrogen produced by steam reforming with CCS in 2040.

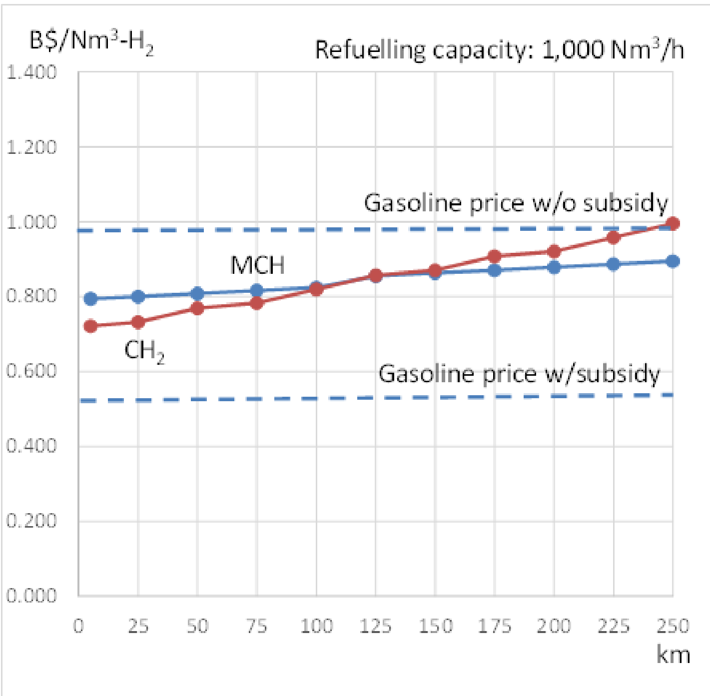
Figure 3.13 shows that up to 230 km, MCH has a higher transport cost than CH_2, and both hydrogen refuelling cost will be higher than gasoline price without subsidy. However, in the case of 1,000 Nm3/h of refuelling capacity, hydrogen refuelling cost will be less than gasoline price without subsidy at 125 km.

Figure 3.13: Transportation Cost of MCH and CH_2 (300 Nm^3/h-H_2)



Source: Author (2020).

Figure 3.14: Transportation Cost of MCH and CH_2 (1,000 Nm^3/h-H_2)



Source: Author (2020).

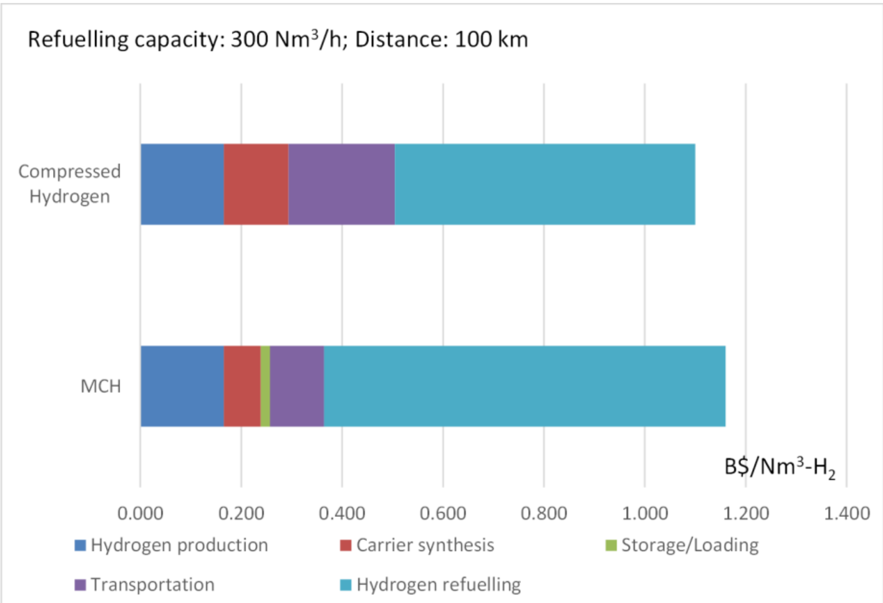
Figures 3.15 and 3.16 compare the component elements of transport cost between MCH and CH_2 at 100 km.

These figures show that major cost components are refuelling station cost for MCH, carrier synthesis, and transportation cost for CH_2 (refuelling station cost for CH_2 is relatively lower than its cost for MCH).

In case of larger hydrogen refuelling station (for e.g. 1,000 Nm^3/h), the cost of hydrogen refuelling station will drastically decrease due to its scale up, and total cost to supply hydrogen at refuelling station of MCH and CH_2 is almost the same.

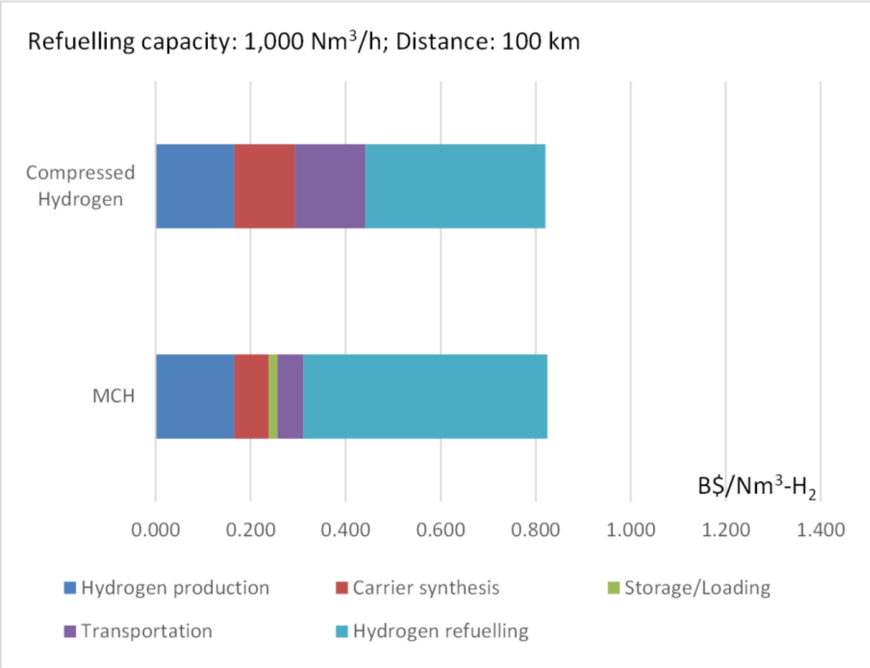
This is because MCH can transport around four times more hydrogen per shuttle compared to CH_2 transportation; in addition, MCH, which is in a liquid state, is easy to handle at ambient conditions and consequently can utilise existing infrastructures similar to the transport of petroleum products.

Figure 3.15:Transportation Cost Components of MCH and CH_2 (300 Nm^3/h-H_2)



Source: Author (2020).

Figure 3.16: Transportation Cost Components of MCH and CH_2 (1,000 Nm^3/h-H_2)

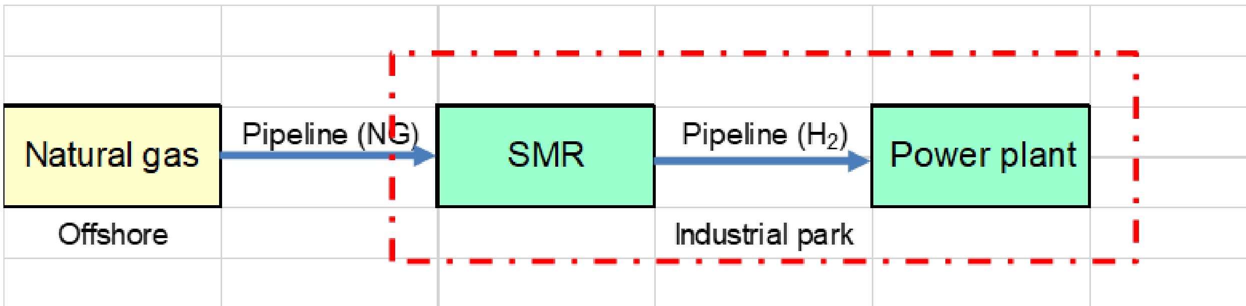


Source: Author (2020).

3.3.3. Hydrogen supply cost for power generation

Hydrogen is also used in Brunei to generate power. Figure 3.17 illustrates a hydrogen supply system from offshore natural gas field to an inland power plant via steam methane reforming (SMR) plant in an industrial park. Existing pipelines are used to transport natural gas between the gas field and the SMR.

Figure 3.17: Hydrogen Supply System for Power Generation



SMR = steam methane reforming.
Source: Author (2020).

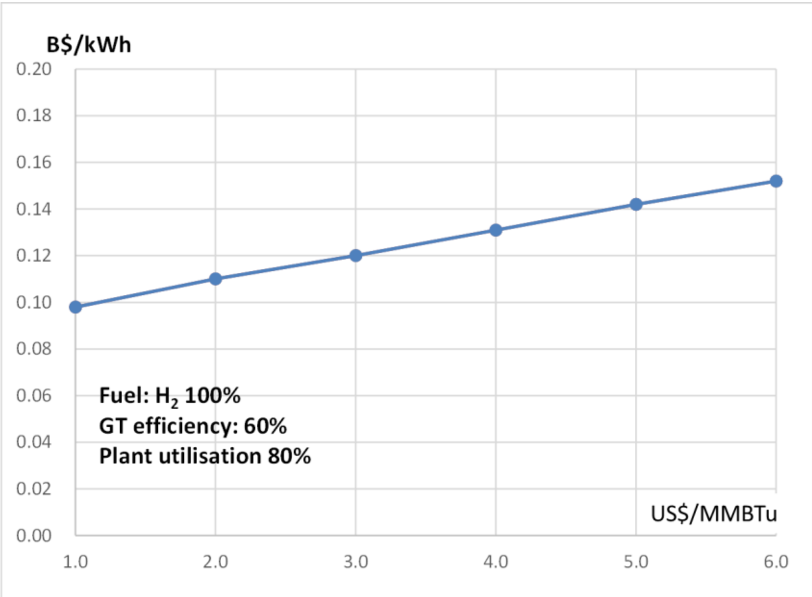
Figure 3.18 shows the correlation between electricity generation cost and natural gas price. The electricity cost estimation is based on hydrogen volume of 600,000 Nm^3/h, which is equivalent to half of the estimated power generation demand (1,252 ktoe per year) of Brunei in 2040.

The costs of hydrogen produced by steam reforming with CCS in 2040 are estimated at B$0.084 and B$0.119 per Nm^3-H_2 for feed natural gas price of US$1.00 and US$3.00 per MMBTu, respectively. The CCS cost in 2040 is assumed to be B$67.00 per tonne of CO_2.

In addition, the power generation output for 600,000 Nm^3/h-H_2 will be around 1,000 MWe using a gas turbine of 60% efficiency.

The electricity generation cost using gas turbine (GT) varies from B$0.10/kWh to B$0.15/kWh as natural gas price changes from US$1.00 to US$6.00 per MMBTu.

Figure 3.18: Electricity Generation Cost Using H_2-GT vs Natural Gas Price



Source: Author (2020).

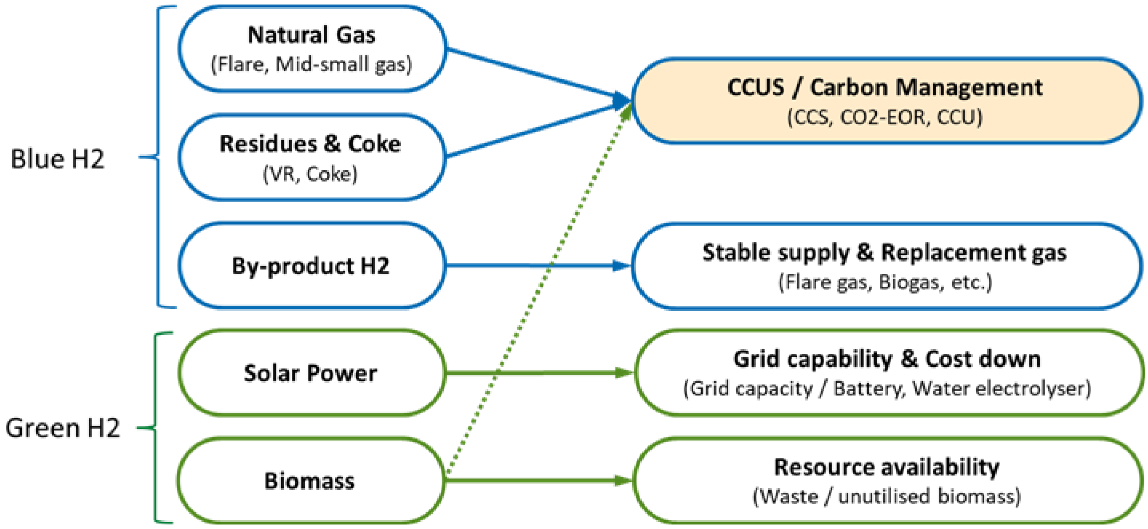
3.4. CO_2 Management

Brunei's total hydrogen production potential is 2.75 Mtoe, 90% of which will be derived from fossil fuels including natural gas reforming and vacuum residue/coke gasification. Production of this fossil fuel–based hydrogen will release around 9.8 million tonnes of CO_2 annually in its process.

To make Brunei's domestic hydrogen-utilising abundant fossil-fuel resources into blue hydrogen, it is crucial to identify the feasibility of carbon management such as CCS, CO_2 enhanced oil recovery (CO_2-EOR) or carbon capture and utilisation (CCU). Blue hydrogen is low-carbon hydrogen derived from non–renewable energy resources (CertifHy n.d.).

Figure 3.19 shows the key requirements for hydrogen to be carbon free.

Figure 3.19: Key Requirements for Carbon-Free Hydrogen



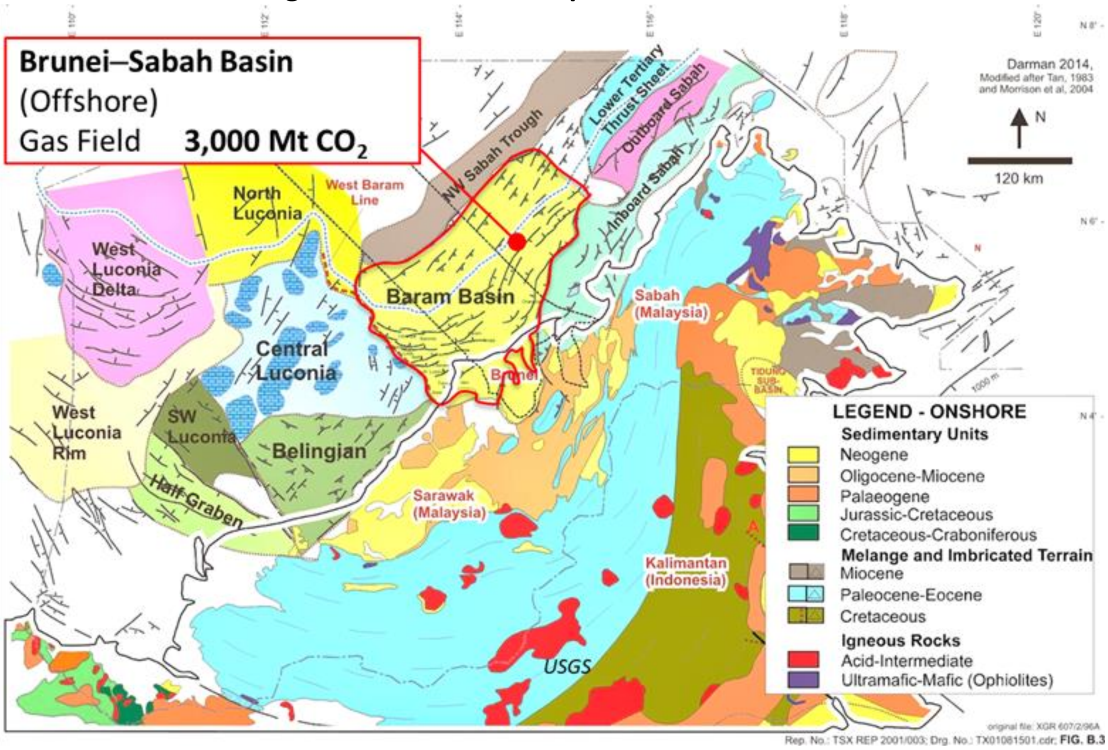
CCU = carbon capture and utilisation, CCUS = carbon capture utilization and storage, CO_2-EOR = carbon dioxide enhanced oil recovery, VR = vacuum residue.
Source: Author (2020).

Brunei Darussalam reportedly has a CCS potential of 3,000 million tonnes of CO_2 in the Brunei–Sabah Basin, the northwest shore and offshore of the country (Consoli, 2016).

And if the country uses CO_2-EOR technology to enhance its oil production in the depleting oil fields, it reportedly has a technically recoverable potential of 1,895 million barrels of oil, for which 559 million tonnes of CO_2 will be required (Godec, 2011).

However, as the Brunei–Sabah Basin is spread across the territorial waters of Malaysia and Brunei, the politico-economic and technical feasibility of related technologies should be considered.

Figure 3.20: Carbon Sequestration Potential



Source: Seismic Atlas of SE Asian Basins (2008).

3.4.1. Carbon capture and utilisation

Other than the sequestration technologies described in the previous section, various kinds of CCU technologies have been gathering attention in industries.

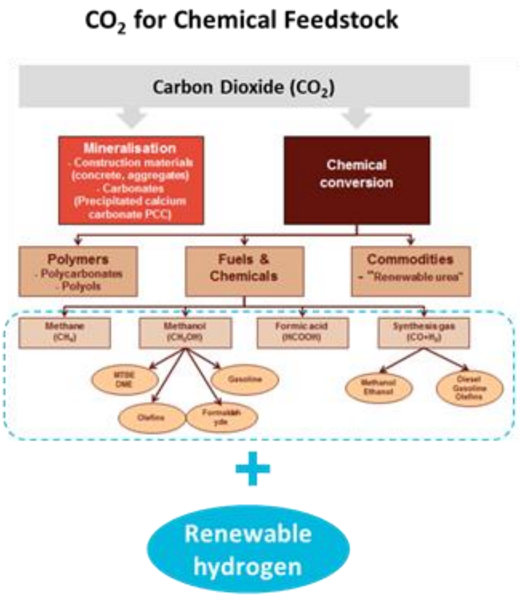
For example, CO_2 can be used as a chemical feedstock in certain chemical production processes by mineralisation or chemical conversions for polymers, fuels, including methane, methanol, formic acid, and synthetic gases and so on (SAPEA, 2018).

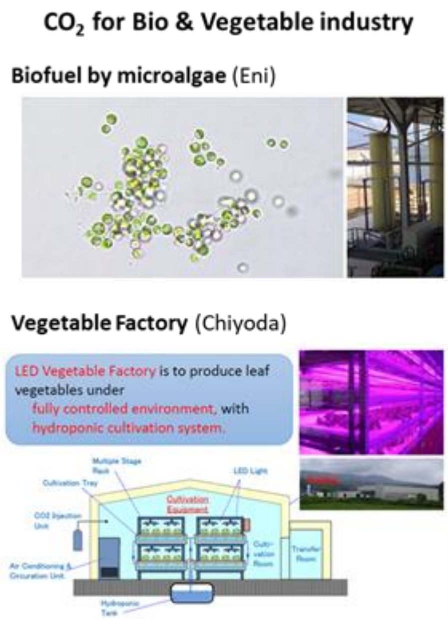
In the biofuel industry, the possibility of CO_2 use to enhance the microalgae cultivation for biofuel production has been investigated (Eni, n.d.).

CO_2 can also be utilised in LED vegetable factories with fully controlled environment to enhance the plant photosynthesis for vegetable production in remote and extreme condition areas (Chiyoda Corporation, 2016).

Although these technologies appear promising, further research and development are required to assess commercial and technical feasibilities.

Figure 3.21: Carbon Capture and Utilisation Examples





Source: SAPEA (2018), Eni, Chiyoda(2016).

CHAPTER 4

Hydrogen Demand Potential in the Road Transport and Power Sectors

4.1. Objectives

The study aims to forecast hydrogen demand in the road transport and power sectors in Brunei Darussalam. For road transport, private vehicle stock was first forecasted until 2040 based on 2009 statistics. Then the results were used to forecast energy demand and emissions for several scenarios. For the power sector, the electricity generation forecast, which was then converted into the corresponding fuel consumption, was first obtained.

4.2. Road Transport Sector

4.2.1. Methodological approach

a. Forecasting future private vehicle stock

The ordinary least squares (OLS) regression method was employed to project future vehicle stock. The population variable was loaded and tested into a commercial statistics software with the stocks of active private vehicles.

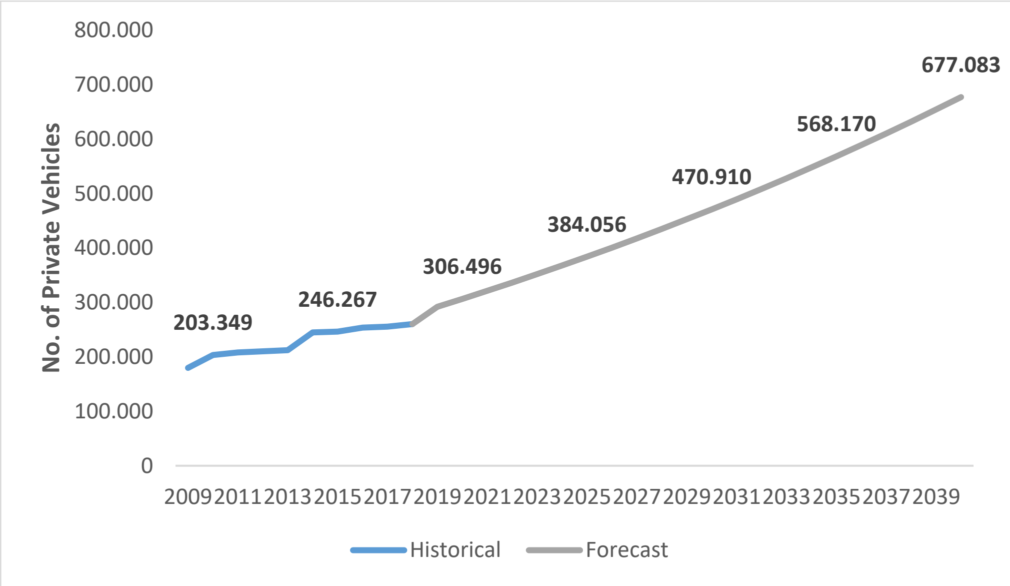
Based on the above tests, the final model is expressed as below:

$$PAV = -340{,}836 + 1.39POP \quad (1)$$

where PAV is the stocks of active private vehicle and POP is population.

Historically, the number of active vehicles grew at 4.2% per year from 179,738 in 2009 to 255,452 in 2017. These vehicles are envisaged to further increase to 677,083 by 2040 at a rate of 4.4% per year (Figure 4.1).

Figure 4.1: Historical and Projected Active Vehicle Stock



Source: Author (2020).

b. Estimating fuel consumption and energy demand

The annual fuel consumption of private vehicles was computed via the following equation:

$$FC_h = PAV_i . ADT . \frac{1}{FE_j} \quad (2)$$

where FC_h is the fuel consumption of fuel type h (litres), PAV_i is the number of active private vehicles of type i, ADT is the average mileage per vehicle (km per year), and FE_j is the fuel economy of vehicle of type j (km per litre). Subsequently from equation (2), this could be converted to energy demand equivalence through:

$$ED_h = \frac{FC_h}{1,000} . \rho_h . \theta_h . 0.0000000041868 \quad (3)$$

where ED_h is the energy demand of fuel type h (TJ), ρ_h is the density of fuel of fuel type h (kg per m^3), and θ_h is the net calorific value of fuel of fuel type h (kcal per kg).

c. Estimating greenhouse gas (GHG) emissions

The corresponding GHG emissions were calculated via the following equation:

$$EM_{nh} = ED_h . EF_{nh} . GWP_n \quad (4)$$

where EM_{nh} is the emission of GHG n from fuel type h (million tonnes CO_2e), EF_{nh} is the emission factor of GHG n from fuel type h (million tonnes per TJ), and GWP_n is the global warming potential of GHG n. The fuel types h considered in this case would be gasoline and diesel, from which carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) are the main GHGs n emitted. As Brunei Darussalam does not have its country-specific EF_{nh}, default values, which were sourced from the Intergovernmental Panel on Climate Change (IPCC), were used (Table 4.1).

Table 4.1: Emission Factors of Gasoline and Diesel Fuels

Fuel Type	**Emission Factor, EF_{nh}**		
	CO_2	**CH_4**	**N_2O**
Gasoline	0.0000693	0.000000033	3.2E–09
Diesel	0.0000741	3.9E–09	3.9E–09

Source: Intergovernmental Panel on Climate Change (IPCC) (2019).

The global warming potential of a GHG, GWP_n, is defined as the total contribution to global warming resulting from the emission of one unit of that gas with respect to one unit of the reference gas (CO_2), which is assigned a value of 1. Based on Table 4.2 below, for example 1 unit of N_2O contributes almost 300 times more than that of CO_2.

Table 4.2: Global Warming Potential of Greenhouse Gases

GHG	**GWP Value**
CO_2	1
CH_4	28
N_2O	265

Source: Intergovernmental Panel on Climate Change (IPCC) (2014).

4.2.2. Scenario description

Several scenarios were constructed in this study. Initially a reference case (business-as-usual scenario [BAU]) was developed to model and forecast consumption and energy demand as well as emissions from conventional fuels without the introduction of fuel cell vehicles (FCVs). The next step was to model and forecast the effect of incorporating FCVs on the energy and emission systems according to FCVs' level of penetration. This case scenario was further subdivided into case 1 (10% penetration), case 2 (30% penetration), and case 3 (50% penetration) (Table 4.3).

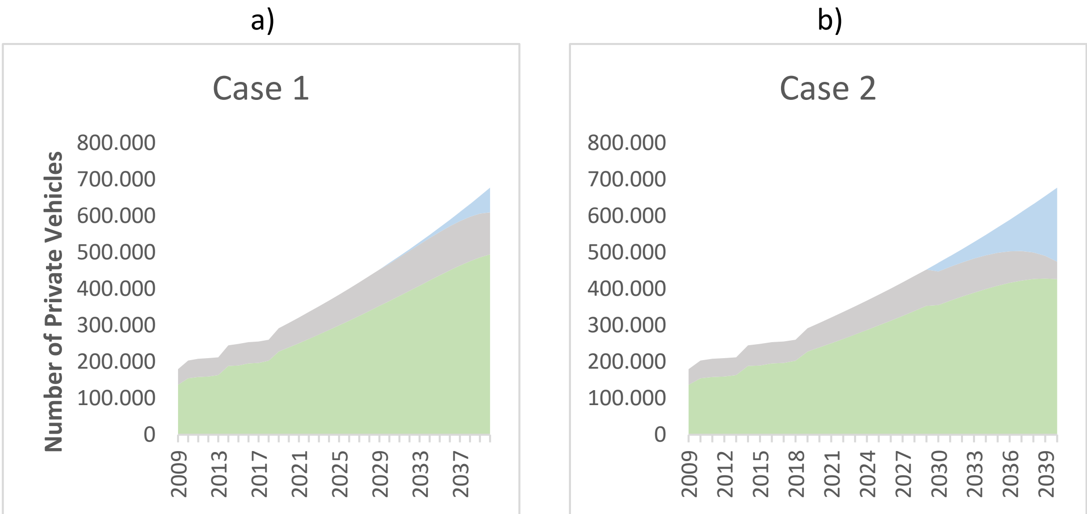
Table 4.3: BAU and FCV Scenarios Considered for Road Transport

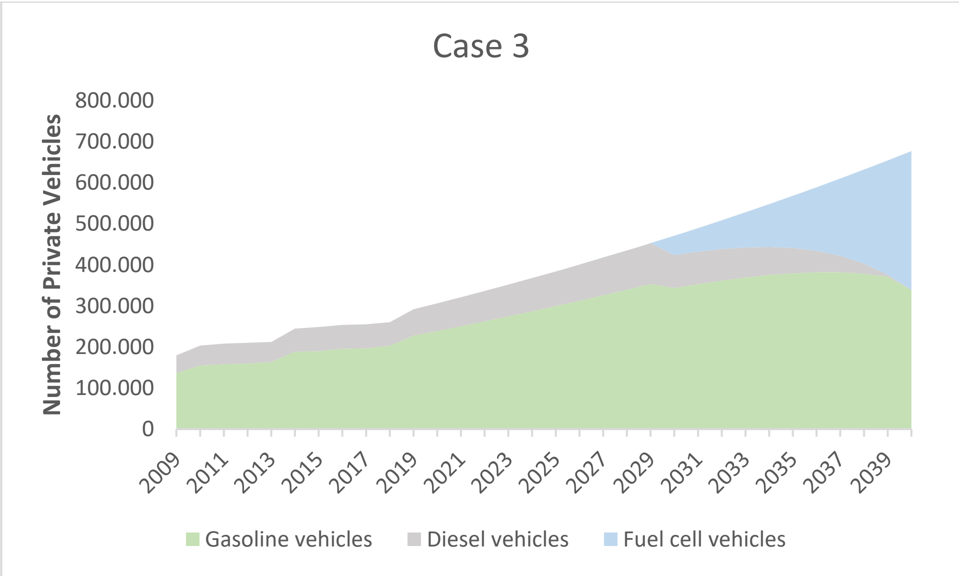
	BAU	Case 1	Case 2	Case 3
FCV introduction	No	Yes	Yes	Yes
FCV introduction year	–	2030	2030	2030
FCV initial penetration	–	1%	5%	10%
FCV target penetration in 2040	–	10%	30%	50%

BAU = business-as-usual scenario, FCV = fuel cell vehicle.
Source: Author (2020).

BAU assumes 78% and 22% shares of gasoline and diesel vehicles, respectively, between now and 2040. Each FCV scenario (Figure 4.2) assumes that the introduction year for a given FCV fleet indicates the starting year of the new buyers' market for FCV of 2030. For case 1, penetration of FCVs would begin at 2,355 vehicles at 1% share, which would reach 67,708 vehicles by 2040. For case 2, FCVs would grow from 23,545 vehicles (5% share) to 203,125 vehicles (30% share) whilst for case 3, FCVs would reach 338,541 vehicles (50% share) from 47,091 vehicles (10% share). With these cases, diesel is assumed to be phased out completely by 2040, as gasoline vehicles and FCVs would be the major fuels by then.

Figure 4.2: Changes in the Scenarios





c)

Source: Author (2020).

4.2.3. Results and discussion

The introduction of hydrogen as an alternative fuel changes the landscape of the road transport sector in terms of final energy consumption and emissions according to variations in scenarios.

a. Hydrogen consumption

Table 4.4 shows gasoline, diesel, and hydrogen consumption in 2040. The total consumption from conventional fuel sources ranges from 484,141 to 755,260 m^3, with case 3 having zero diesel consumption. Hydrogen consumption ranges from 20,566 tonnes (58.79 ktoe) to 102,832 tonnes (293.97 ktoe).

Table 4.4: Gasoline, Diesel, and Hydrogen Consumption (2040)

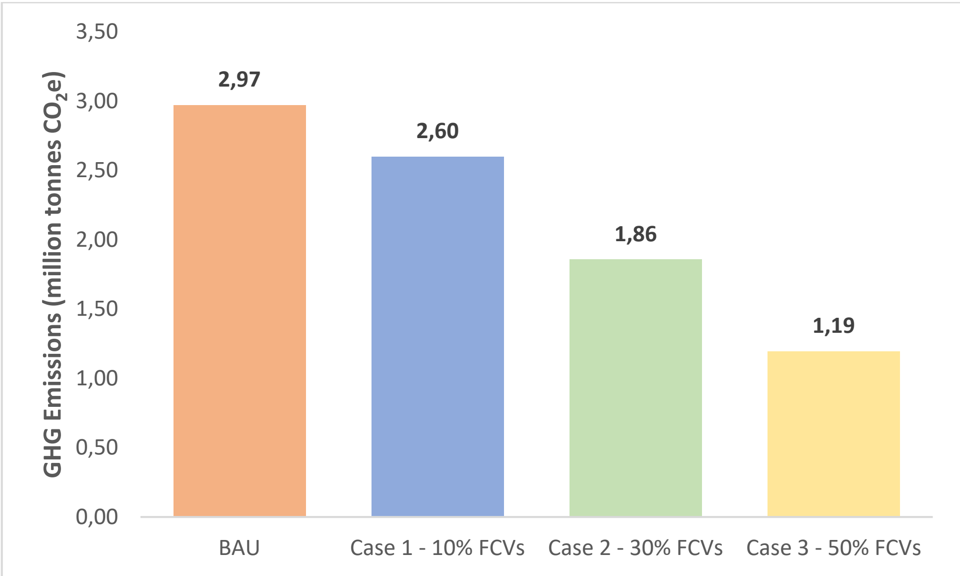
Fuel Consumption	Unit	Business-As-Usual Scenario	Case 1	Case 2	Case 3
Gasoline	m^3	755,260	706,846	610,017	484,141
Diesel	m^3	395,861	305,893	125,956	0
Gasoline and diesel	m^3	1,151,121	1,012,738	735,973	484,141
Hydrogen	Nm^3	–	228,769,285	686,307,854	1,143,846,423
	ktoe	–	58.79	176.38	293.97
	tonne	–	20,566	61,699	102,832

Source: Author (2020).

b. Reduction of GHG emissions

Figure 4.3 schematically illustrates the GHG emissions from the road transport sector for these scenarios. Emissions from BAU are envisaged to reach approximately 2.97 million tonnes CO_2e. With 10% FCVs, emissions would be reduced by 12% to 2.60 million tonnes CO_2e compared to BAU. Reductions of 37% and 60% would be projected with 30% and 50% FCVs, respectively.

Figure 4.3: Projected Greenhouse Gas Emissions Compared to BAU (2040)



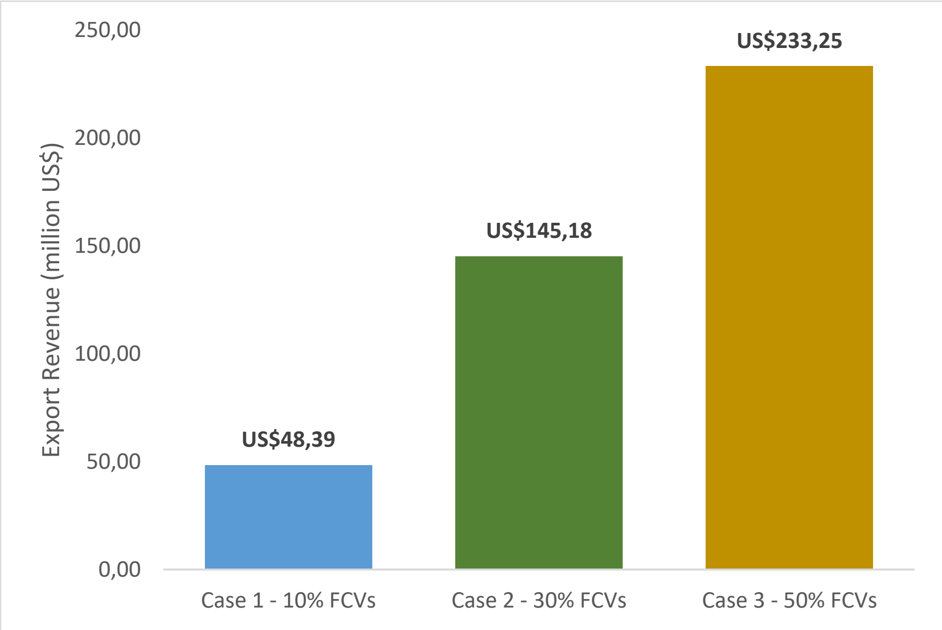
BAU = business-as-usual, FCV = fuel cell vehicle, GHG = greenhouse gas.
Source: Author (2020).

c. Crude oil export revenue

The introduction of hydrogen in the road transport sector could also potentially influence export revenue from crude oil as a result of fuel savings. Assuming the average price of crude oil in 2040 hovers at US$55.60 per barrel (World Bank, 2020),[2] potentially Brunei Darussalam could export additional crude oil; that extra revenue will range from US$48.70 million to US$233.25 million by 2040 (Figure 4.4).

[2] The author assumes that this price stays on a level with the 2035's forecasted price the World Bank.

Figure 4.4: Potential Crude Oil Export Revenue (2040)



FCV = fuel cell vehicle.
Source: Author (2020).

4.3. Power Sector

4.3.1. Methodological approach

a. Forecasting electricity generation

The country's overall electricity generation is envisaged to grow to 17.76 TWh by 2040 under BAU (ERIA, 2019). Electricity from natural gas will account for about 79% of the total generation, whilst coal and oil will contribute to 20.5% and 0.16%, respectively. Under the alternative policy scenario (APS) in the same year, 13.08 TWh of electricity is forecasted and the reduction is due to the inclusion of 0.9 TWh of renewable energy, as well as the decommissioning of the diesel power plants in Temburong in 2021 and the improvement in efficiency in all power stations (ERIA, 2019).

b. Estimating hydrogen gas consumption

Hydrogen consumption from a gas turbine can be estimated via the following equation:

$$HC_{Energy} = EG\ x\ HR\ x\ \alpha \qquad (5)$$

where HC_{Energy} is the hydrogen consumption (energy form) (MJ), EG is the electricity generated from the gas turbine, HR is the average heat rate of gas turbine, and α is the calorific percentage of hydrogen in the gas turbine. Subsequently from equation (5), this could be converted to volumetric consumption equivalence through:

$$HC_{Volume} = \frac{HC_{Energy}\, x\, \frac{1}{HCal}}{1{,}000}$$
(6)

where HC_{Volume} is the hydrogen consumption (volumetric form) (thousand m^3), and $HCal$ is the calorific value of hydrogen (lower calorific value). The value of $HCal$ is assumed to be 10.7 MJ per m^3.

c. Estimating GHG emissions

Similar to those in the road transport sector, the corresponding GHG emissions were calculated via the following equation:

$$EM_{nh} = ED_h . EF_{nh} . GWP_n$$
(7)

where EM_{nh} is the emission of GHG n from fuel type h (million tonnes CO_2e), EF_{nh} is the emission factor of GHG n from fuel type h (million tonnes per TJ), and GWP_n is the global warming potential of GHG n. The fuel type h considered in this case would be natural gas, from which carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) are the main GHGs n emitted. As Brunei Darussalam does not have its country-specific EF_{nh}, default values, which were sourced from the IPCC, were used (Table 4.5).

Table4.5: Emission Factors of Natural Gas

Fuel Type	Emission Factor, EF_{nh}		
	CO_2	CH_4	N_2O
Natural Gas	0.0000561	0.000000001	0.0000000001

Source: Intergovernmental Panel on Climate Change (IPCC) (2007).

4.3.2. Scenario description

The development of scenarios in this section is similar to that for road transport, albeit with different set parameters. The reference case (BAU) was developed based on power stations' consuming 100% natural gas and operating at present efficiency. The other three scenarios – cases 1 to 3 – were developed based on the conditions shown in Table 4.6. All the scenarios would have the initial penetration of 5% hydrogen (calorific percentage α) and would be further progressed depending on each scenario's conditions (Tables 4.7, 4.8, and 4.9). It should be noted that for case 1, there is no development of a new gas turbine construction as the hydrogen would be mixed only in the existing turbines. Such development would only be considered in cases 2 and 3.

Table4.6: BAU and Case Scenarios Considered for the Power Sector

	BAU	Case 1	Case 2	Case 3
Hydrogen	No	Yes	Yes	Yes
Hydrogen Introduction Year	–	2035	2035	2035
Hydrogen Initial Penetration	–	5%	5%	5%
Hydrogen Target Penetration 2040	–	10%	30%	50%
Power Plant Efficiency	30%	30%	60%	60%

Source: Author (2020).

Table4.7: Calorific Percentages of Natural Gas and Hydrogen for Case 1 Scenario

Year	Natural Gas	Hydrogen
2035	95%	5%
2036	94%	6%
2037	93%	7%
2038	92%	8%
2039	91%	9%
2040	90%	10%

Source: Author (2020).

Table 4.8: Calorific Percentages of Natural Gas and Hydrogen for Case 2 Scenario

Year	Natural Gas	Hydrogen
2035	95%	5%
2036	90%	10%
2037	85%	15%
2038	80%	20%
2039	75%	25%
2040	70%	30%

Source: Author (2020).

Table 4.9: Calorific Percentages of Natural Gas and Hydrogen for Case 3 Scenario

Year	Natural Gas	Hydrogen
2035	95%	5%
2036	90%	10%
2037	80%	20%
2038	70%	30%
2039	60%	45%
2040	50%	50%

Source: Author (2020).

4.3.3. Results

a. Hydrogen consumption

Table 4.10 shows the natural gas and hydrogen consumption in 2040. The total consumption from natural gas ranges from 3,912 million m^3 (4,318 ktoe) to 5,749 million m^3 (4,788 ktoe). Hydrogen consumption ranges from 258 million m^3 (66 ktoe) to 1,837 million m^3 (470 ktoe).

Table 4.10: Natural Gas and Hydrogen Consumption (2040)

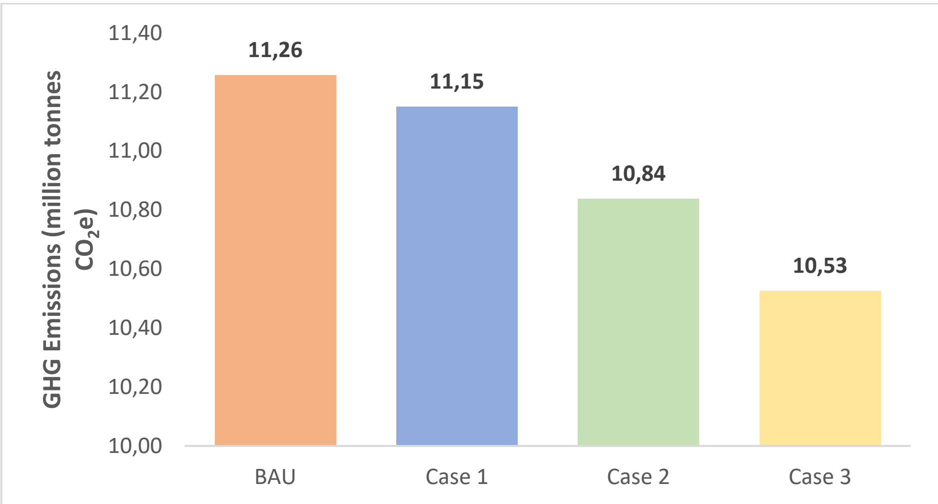
Fuel Consumption	Unit	BAU	Case 1	Case 2	Case 3
Natural gas	million m^3	5,749	5,670	4,647	3,912
	ktoe	4,788	4,722	4,506	4,318
Hydrogen	million m^3	–	258	1,102	1,837
	ktoe	–	66	282	470

BAU = business-as-usual scenario.
Source: Author (2020).

b. Reduction of GHG emissions

Figure 4.5 schematically illustrates the GHG emissions from the power sector for these scenarios. Emissions from BAU are envisaged to reach approximately 11.26 million tonnes CO_2e. With case 1, emissions would be reduced by 1.0% to 11.15 million tonnes CO_2e compared to BAU. Reductions by 3.7% and 6.5% would be projected in cases 2 and 3, respectively.

Figure 4.5: Projected Greenhouse Gas Emissions Compared to BAU (2040)

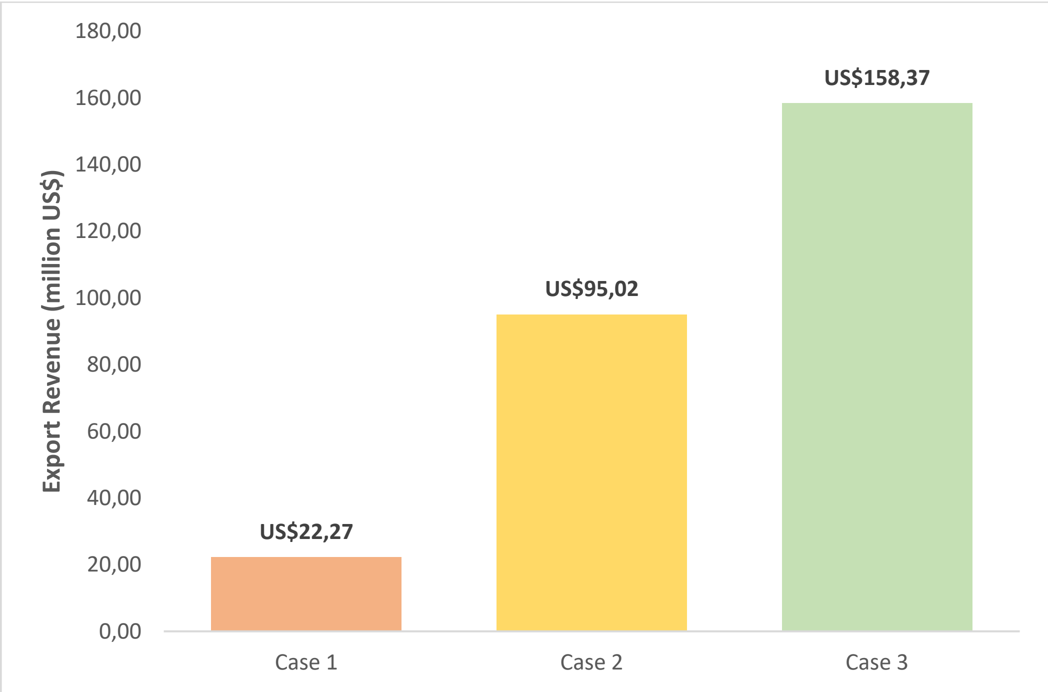


BAU = business-as-usual scenario.
Source: Author (2020).

c. Export revenue from liquefied natural gas

Similar to road transport, the effect of hydrogen introduction in the power sector is the significant increase in the export of liquefied natural gas (LNG). Again, assuming the average price of LNG in 2040 is US$8.50 per MMBTu (World Bank, 2020), Brunei Darussalam could gain additional revenue ranging from US$22.27 million to US$158.37 million by 2040 (Figure 4.6).

Figure 4.6: Potential Natural Gas Export Revenue (2040)



Source: Author (2020).

CHAPTER 5

Hydrogen Supply and Demand Balance and Proposed Models

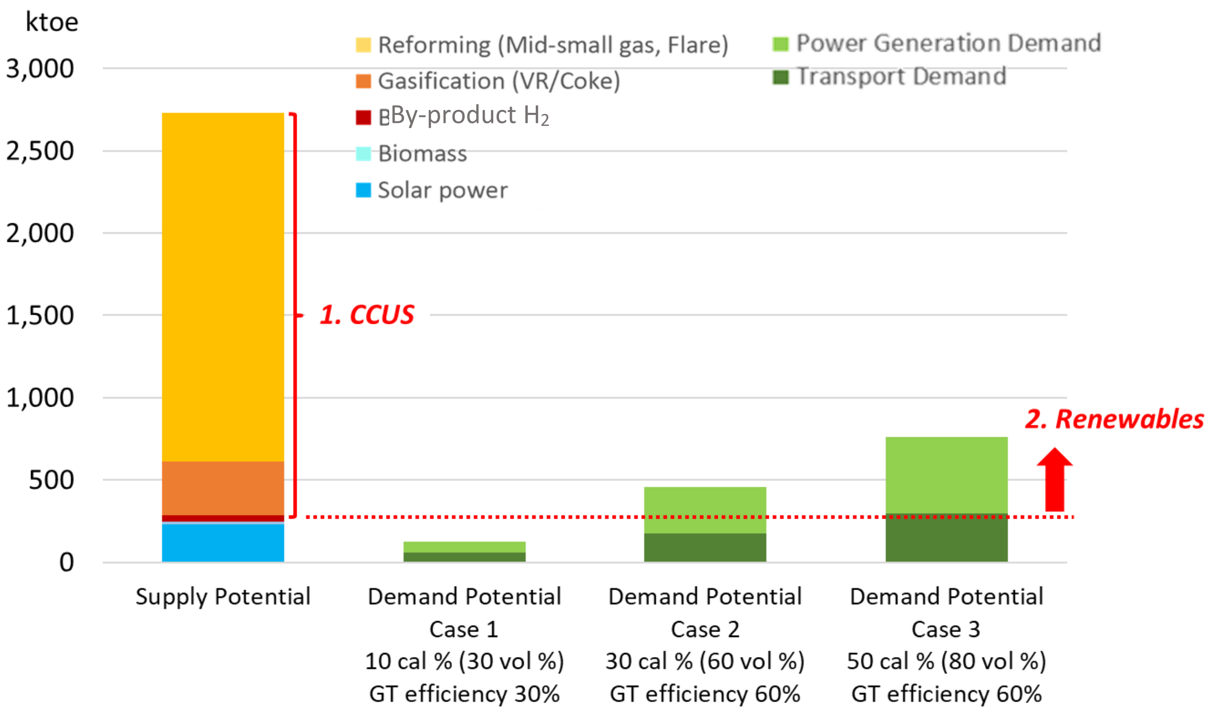
5.1. Hydrogen Balance in 2040

Figure 5.1 shows the hydrogen supply and demand balance of Brunei in 2040. We set the three scenarios (cases 1, 2, and 3) with 10, 30, and 50 calorific percentage of hydrogen penetration into the country's energy market to see the hydrogen supply and demand balances (Table 5.1).

The graph shows that there is enough potential in hydrogen production to fulfil the expected hydrogen demand in 2040 in Brunei Darussalam.

The large portion of the hydrogen supply potential will come from fossil fuels which require carbon capture and storage (CCS)/carbon capture and utilisation (CCU) technologies to make the hydrogen blue. However, with the expansion of renewable energies in the future, Brunei can potentially increase the volume and sustainability of hydrogen supply.

Figure 5.1: Hydrogen Supply and Demand Balance in 2040



GT = gas turbine, VR = vacuum residue.
Source: Author (2020).

Table 5.1: Hydrogen Penetration Scenario

	Power Generation (Calorie %) -> kWh			FCVs (Calorie %) -> km	
		NG	H_2	Gasoline /Diesel	H_2
Base	GT Efficiency 30%	100%	0%	100%	0%
Case 1	**Existing GT** 30 vol % co-fire, Efficiency 30%	90 cal %	10 cal % (30 vol %)	90%	10%
Case 2	**New Construction GT** 60 vol % co-fire, Efficiency 60%	70 cal %	30 cal % (60 vol %)	70%	30%
Case 3	**New Construction GT** 80 vol % co-fire, Efficiency 60%	50 cal %	50 cal % (80 vol %)	50%	50%

Source: Author (2020).

As a whole, Brunei Darussalam has a hydrogen supply potential of 2.7 Mtoe, with fossil fuel–derived hydrogen accounting for 90% of the total. On the other hand, in demand scenario case 1 (10% calorie of hydrogen), the hydrogen demand is estimated at 0.12 Mtoe; in case 2 (30% calorie), it is 0.46 Mtoe; and in case 3 (50% calorie), 0.76 Mtoe.

Considering the above circumstances, the feasibility of CCS, CO_2-enhanced oil recovery (EOR), and CCU applications for fossil fuel–derived hydrogen production and the significant increase of renewable energy production will play a central role in fulfilling the country's hydrogen demand in the future.

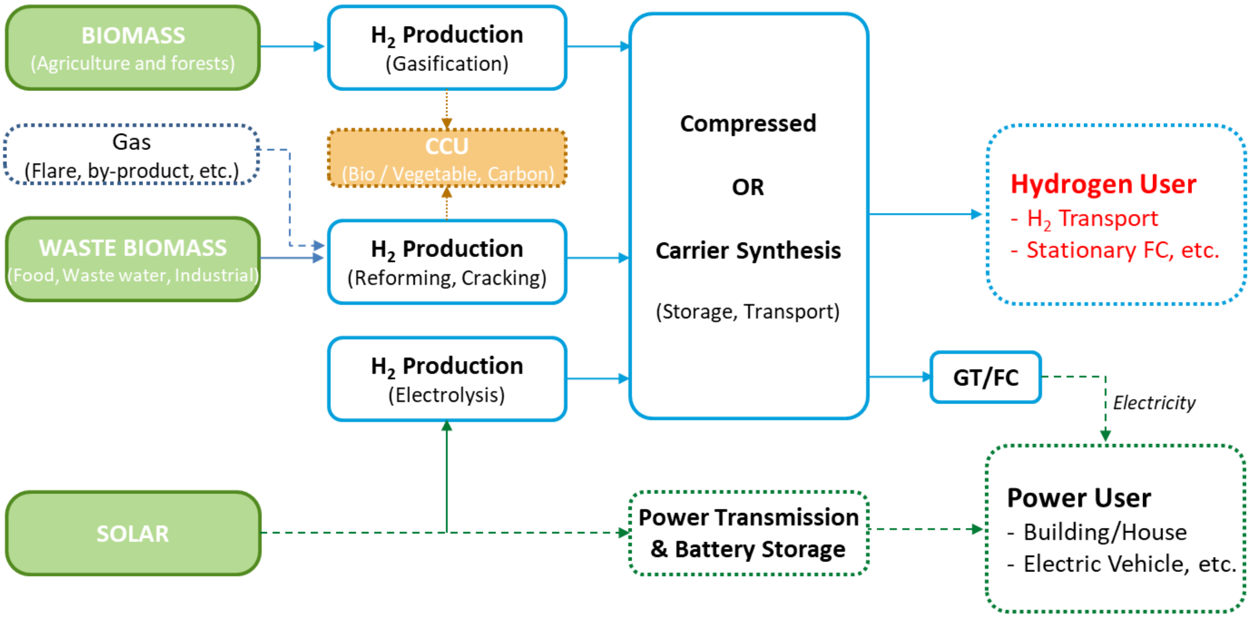
5.2. Proposed Hydrogen Penetration Models

To enhance the smooth penetration of hydrogen into Brunei's energy market, various models could be envisaged as hydrogen supply and demand models.

- ***Hydrogen Supply Model: Domestic Hydrogen Supply Chain in Brunei Darussalam***

To establish the domestic hydrogen supply chain, the key points will be to maximise the use of domestic renewable resources (green hydrogen) for both the power and transport sectors, and minimise the use of fossil fuel–based energy (blue hydrogen) for decarbonisation and maximise the benefits and sustainability of fossil fuel resources.

Figure 5.2: Hydrogen Supply Model: Domestic Hydrogen Supply Chain in Brunei Darussalam

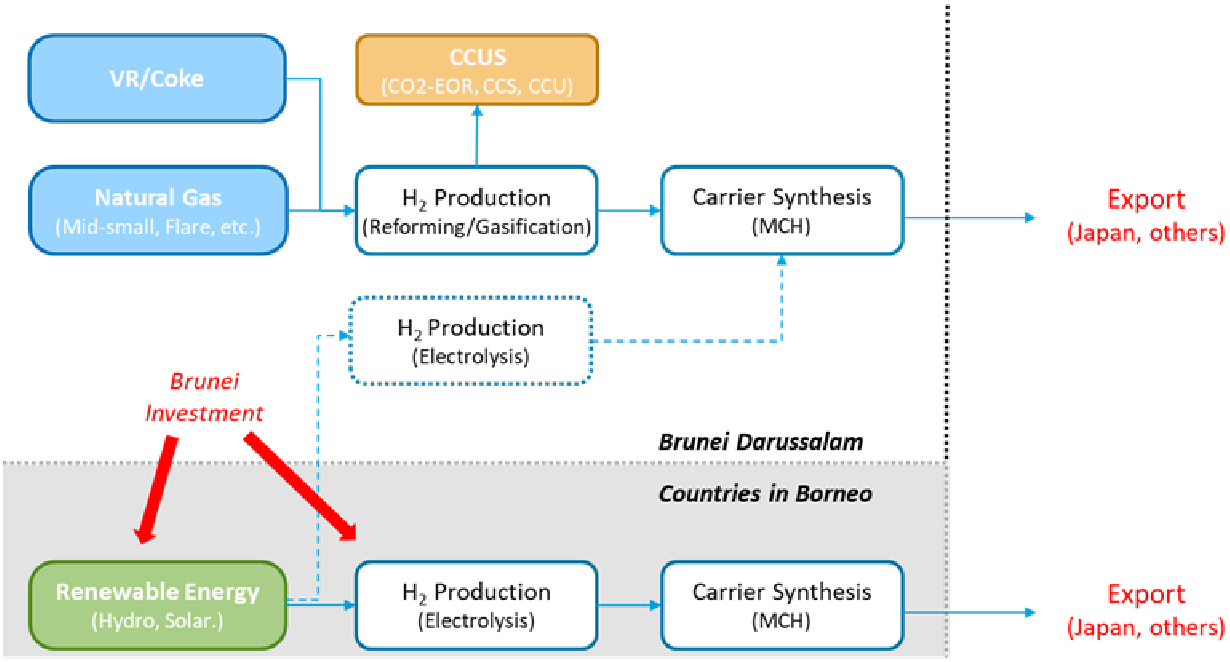


CCU = carbon capture and utilisation.
Source: Author (2020).

- ***Hydrogen Supply Model: Global Hydrogen Supply Chain from Brunei Darussalam***

Key points to establish a global hydrogen supply chain is the use of CCU technologies for fossil fuel–based hydrogen. Another option is the use of abundant renewable energy outside of Brunei Darussalam, with strategic investment for cross-bordering import of renewable energy in some cases, in collaboration with neighbour countries of Borneo.

Figure 5.3: Hydrogen Supply Model: Global Hydrogen Supply Chain from Brunei Darussalam



CCS = carbon capture and storage, CCU = carbon capture and utilisation, CCUS = carbon capture utilisation and storage, MCH = methylcyclohexane, VR = vacuum residue.
Source: Author (2020).

- ***Hydrogen Demand Model: Hydrogen Transportation***

There are also opportunities to introduce hydrogen-based buses, trucks, hydrogen fuel cell electric vehicles (FCEVs) and/or public transport systems such as bus rapid transportation (BRT)/light rail transit (LRT), to reduce fossil fuel consumption and CO_2 emissions from the transport sector of Brunei.

Figure 5.4: Hydrogen Demand Model: Hydrogen Transportation

Fuel Cell BRT system

(e.g. France: The world's first hydrogen-powered BRT)

Eight 18 meter long Van Hool fuel cell buses operate 6 km express route.

Fuel Cell LRT system

(e.g. Sarawak: Kuching LRT ready by 2024)

BRT = bus rapid transit, LRT = light rail transit.
Source: Smart Cities World (2019) (left); KUCHINGBORNEO (2018) (right).

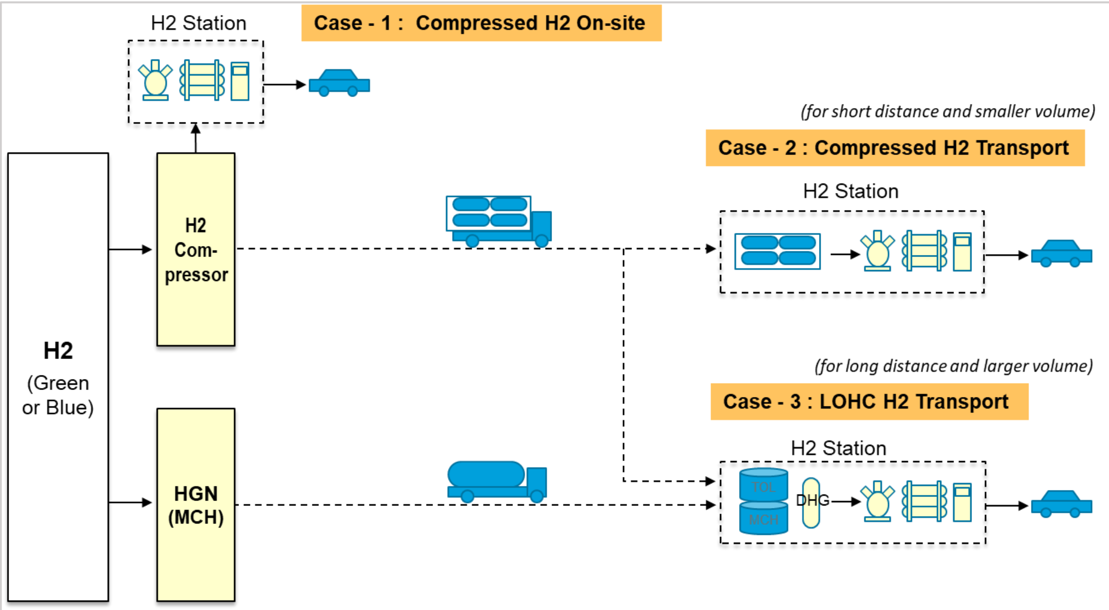
FCEVs will play an important role in decarbonising the transport sector. Gasoline and diesel are reported to account for 21% of global carbon emission (Hydrogen Council, 2017). The introduction of hydrogen into the mobility sector will significantly reduce CO_2 emissions in the transport sector.

FCEVs demonstrate their strength especially in the use of heavier duty vehicles (over 100 km per day, 10 tonnes) such as medium-to-large cars, trucks, buses, and BRT and LRT systems. FCEVs will potentially contribute to reducing the government's fuel subsidy of B$180 million–B$400 million annually. Decreasing domestic gasoline and diesel consumption can also increase the country's oil and gas export.

- ***Hydrogen Demand Model: Hydrogen Transportation (H_2 Refuelling Station)***

There are several options for hydrogen refuelling stations, such as onsite hydrogen generation and refuelling system, compressed hydrogen refuelling station, and liquid organic hydrogen carrier methylcyclohexane (MCH) refuelling station, with hydrogen transport and larger hydrogen production and to be selected depending on the location, volume of hydrogen sources, grid infrastructure, etc.

Figure 5.5: Hydrogen Demand Model: Hydrogen Transportation Model (H_2 Refuelling Station)

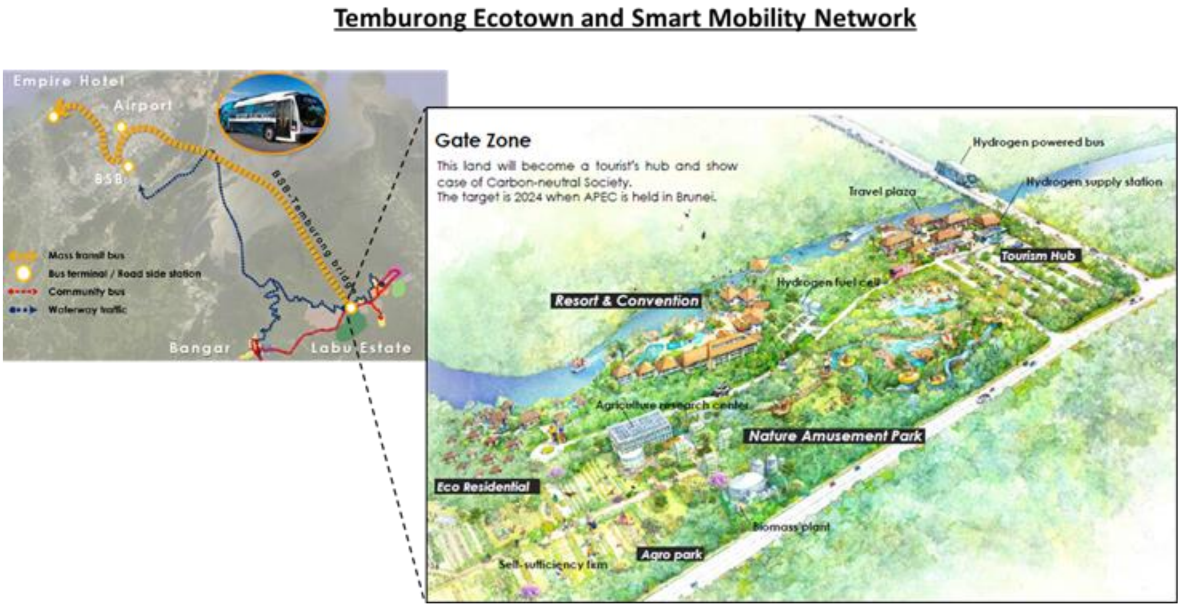


LOHC = liquid organic hydrogen carrier, MCH = methylcyclohexane.
Source: Author (2020).

- ***Hydrogen Demand Model: Ecotown (Renewable and Hydrogen Energy System)***

There is opportunity to build an eco-friendly and innovative town using hydrogen technology as one of the key alternatives for a sustainable town model in Southeast Asia.

Figure 5.6: Hydrogen Demand Model: Ecotown (Renewable and Hydrogen Energy System)



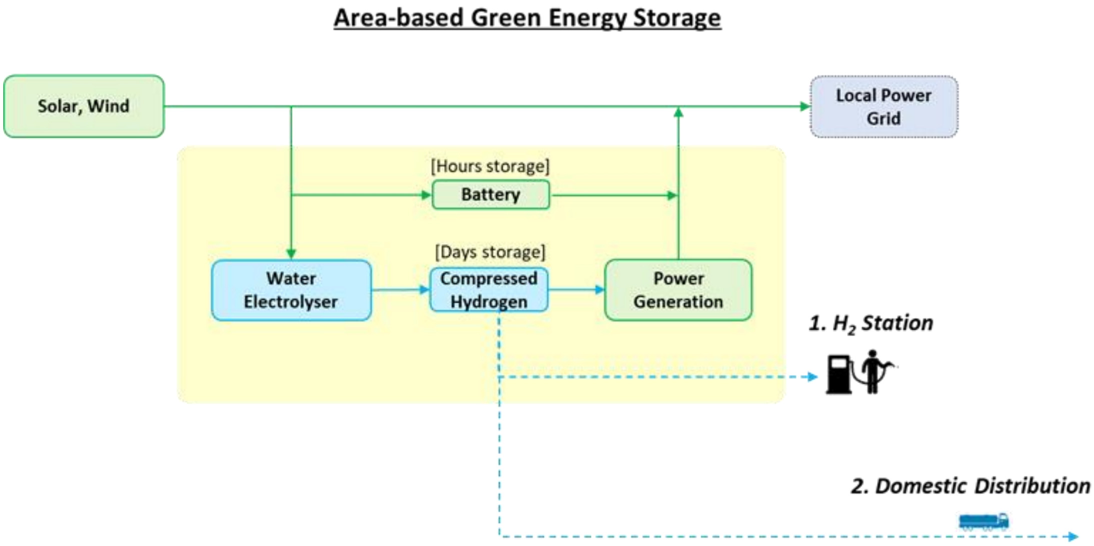
APEC = Asia-Pacific Economic Cooperation.

Source: ERIA and Nikken Sekkei Civil Engineering Ltd (2019).

- ***Hydrogen Demand Model: Ecotown (Area-based Green Storage System)***

To supply stable renewable energy in remote areas, like the Temburong district, it will be valuable to install the integrated battery and hydrogen storage and transport system that will become a part of the hydrogen network.

Figure 5.7: Hydrogen Demand Model: Ecotown (Area-based Green Storage System)

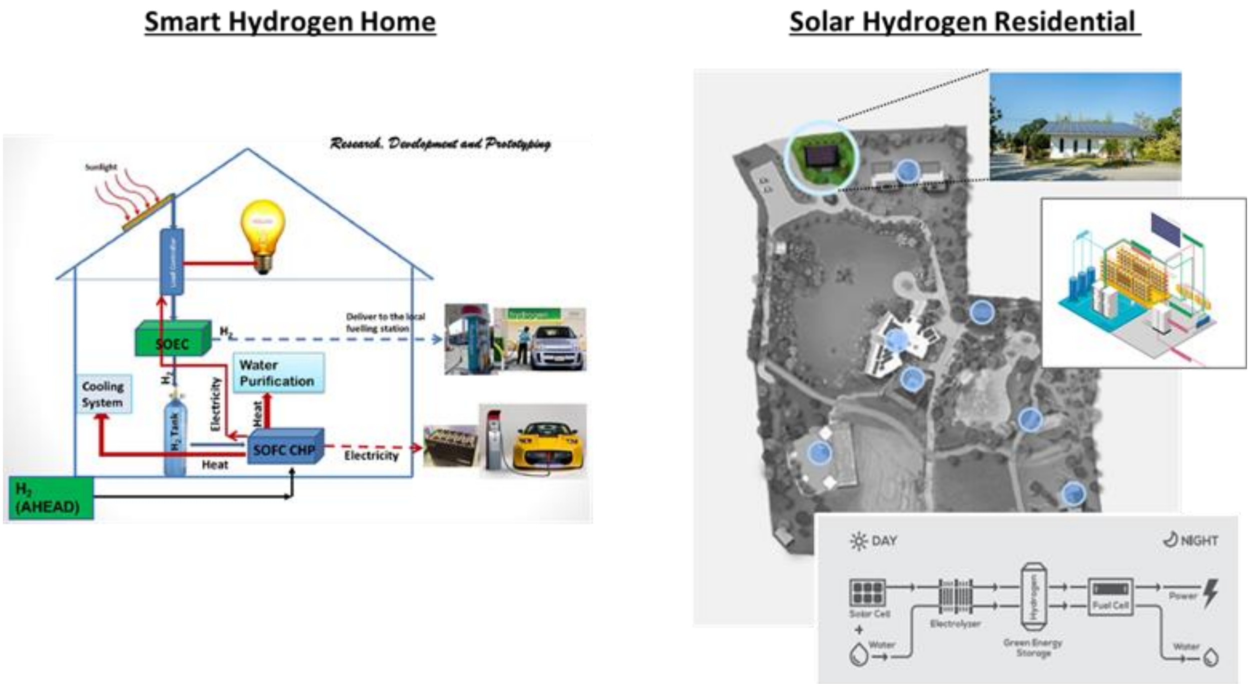


Source: Author (2020).

- ***Hydrogen Demand Model: Ecotown (Home Storage System)***

Another application is an integration system of solar, battery, and hydrogen storage for lower or zero CO_2 emissions and stable green energy supply to the residential zone.

Figure 5.8: Hydrogen Demand Model: Ecotown (Home Storage System)



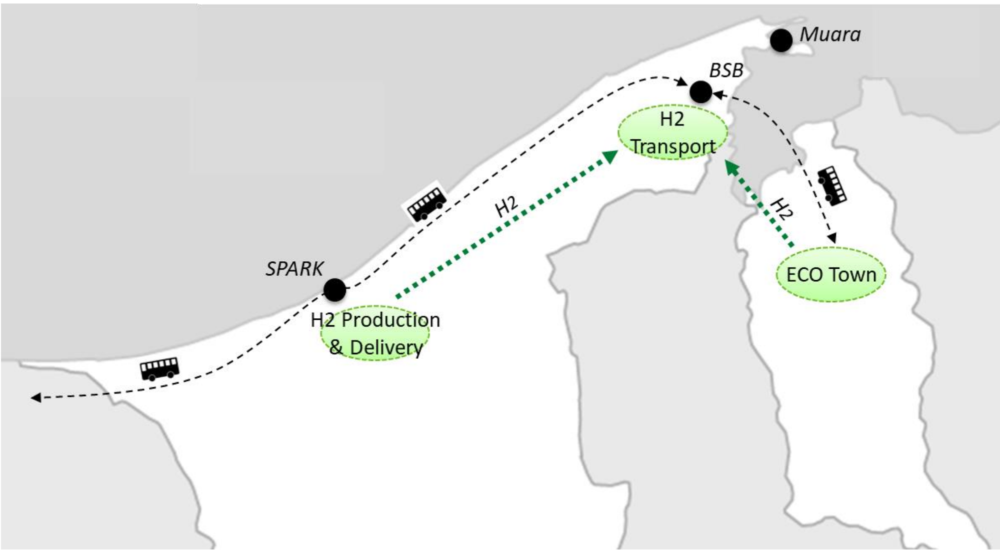
Source: Azad (2018) (left); Phi Suea House (2020) (right).

- ***Hydrogen Demand Model: Example Projects***

There are several opportunities to introduce hydrogen, and the following are examples of hydrogen projects in Brunei Darussalam:

- Hydrogen transportation in Bandar Seri Begawan, using the BRT system and FCEVs
- Temburong ecotown, utilising solar hydrogen storage
- Hydrogen production and delivery at Sungai Liang Industrial Park (SPARK), Belait district, utilising steam methane reforming and electrolysis, and compression of MCH.

Figure 5.9: Hydrogen Demand Model: Example Projects



Source: Author (2020).

CHAPTER 6

Conclusions and Policy Recommendations

This chapter presents the conclusions of and recommendations from the study:

1. Brunei Darussalam is a gas-rich country, and the potential of producing hydrogen from gas will clearly be significant, according to this study. But to pay attention to climate change issues, zero emission measures such as CO_2-enhanced oil recovery (EOR) and carbon capture utilisation and storage (CCUS) will be applied once available technically and affordably.

2. On the other hand, large potential of hydrogen demand in Brunei Darussalam will be forecasted in both the transport, especially road, and the power generation sectors. Shifting to hydrogen from oil and gas will provide the country with two benefits: (i) significant reduction of CO_2 emissions and (ii) economic benefits from increased oil and gas exports.

3. But shifting to a hydrogen society in both demand and supply sides requires lots of efforts:
    - Appropriate hydrogen policies both demand and supply sides
    - Action plans to shift from internal combustion engine to fuel cell electric vehicle (FCEV), including incentives
    - Action plans to increase hydrogen mixing rate at existing gas power plants
    - Action plans to hydrogen supply chain in Brunei Darussalam, such as hydrogen charging stations
    - Action plans to continue hydrogen export to Asian countries
    - To shift from internal combustion engine to FCEV, FCEV can demonstrate its strength, especially in the use of heavier duty vehicles (over 100 km/day, 10 tonnes) such as medium-to-large cars, trucks, buses, and bus rapid transit (BRT) and light rail transit (LRT) systems.
    - In the future, hydrogen sources in Brunei Darussalam will shift from fossil fuels to renewable energy. In other words, grey and blue hydrogen will change to green hydrogen. The country could also consider increasing renewable energy supply through cross-border collaboration with Borneo as an option.
4. Hydrogen production and supply cost is essential.
    - The shift to a hydrogen society is fully dependent on hydrogen production and supply cost. In this regard, the introduction of hydrogen in the market, government policy and support – such as national future visions – funding and market supporting mechanisms, research and development promotions, awareness programmes, international cooperation, etc. can be strong drivers.

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