Chapter 3

Potential of Hydrogen Production

June 2020

This chapter should be cited as

ERIA, BNERI and Chiyoda Corporation (2020), 'Potential of Hydrogen Production', in *Brunei Darussalam: Shifting to Hydrogen Society.* ERIA Research Project Report FY2020 no.04, Jakarta: ERIA, pp.9-28.

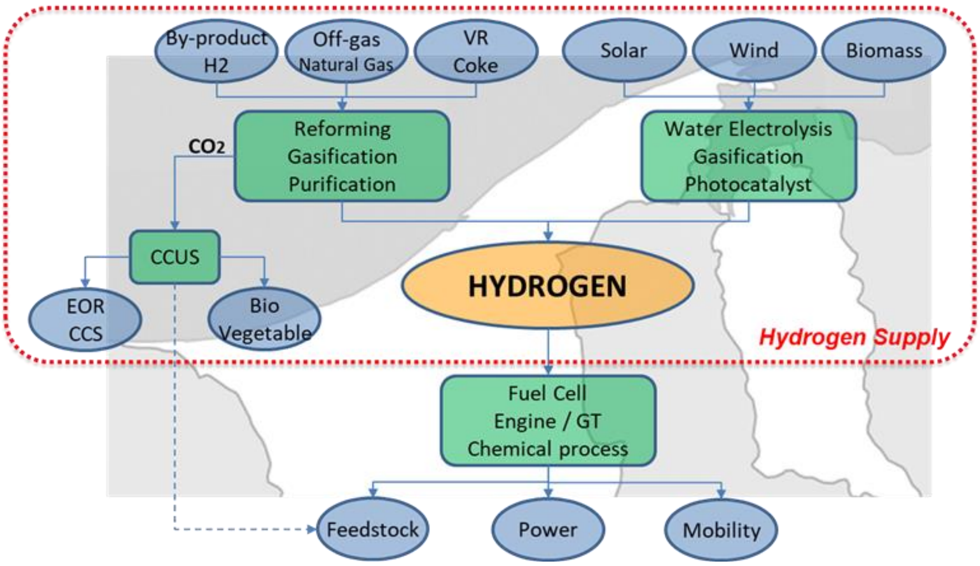
CHAPTER 3

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.

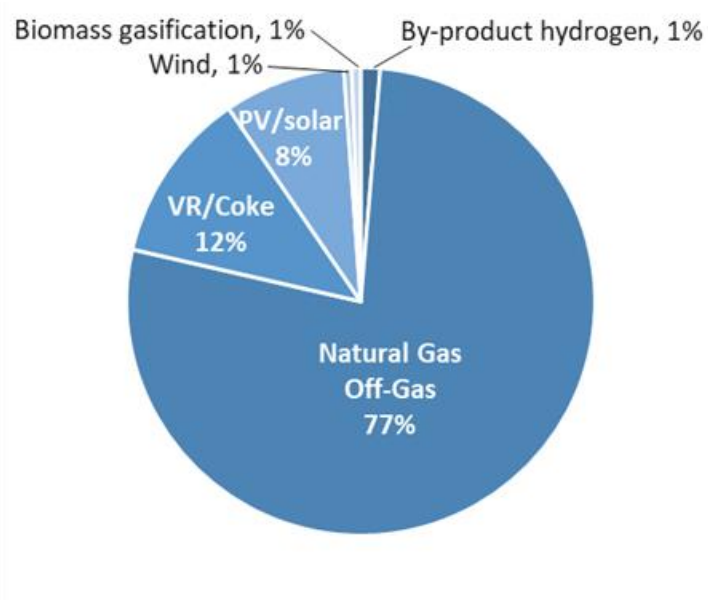
On renewable energy–derived hydrogen, renewable electricity such as solar, wind, hydro, and geothermal can be converted into hydrogen through water electrolysis technology, and biomass can produce hydrogen by using gasification technology.

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).

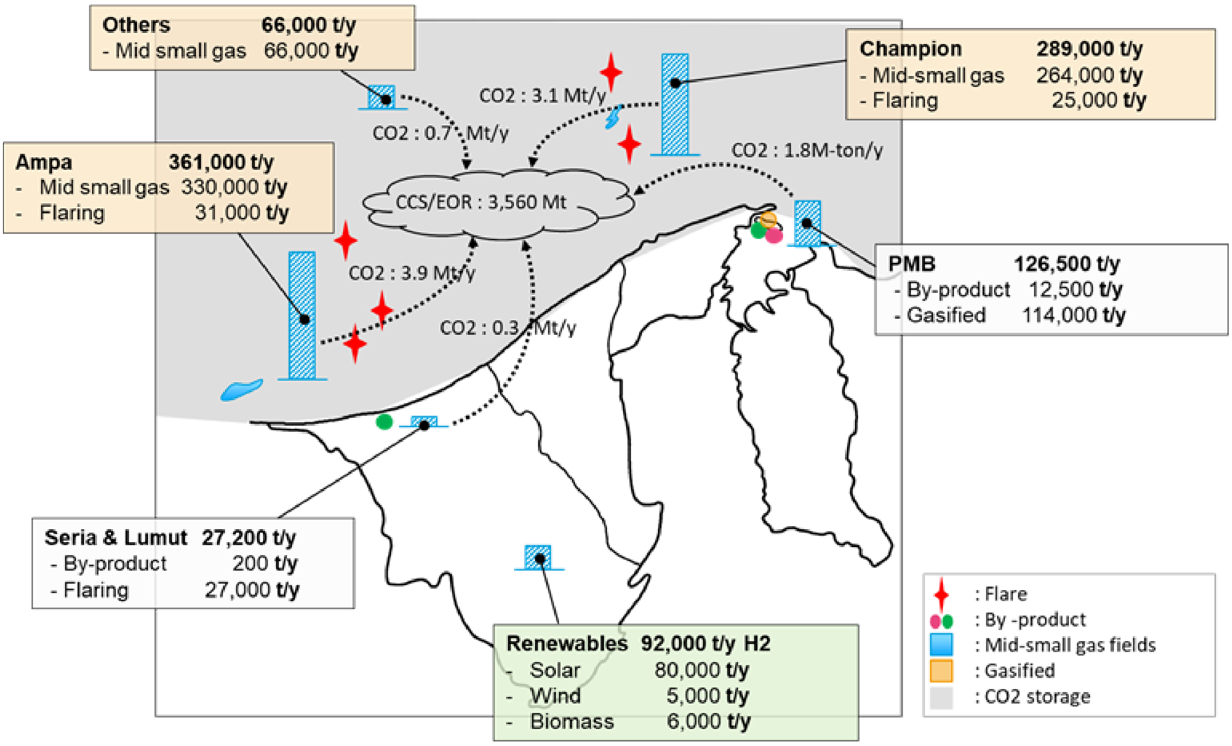
Figure 3.2: Hydrogen Production Potential, by Source



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

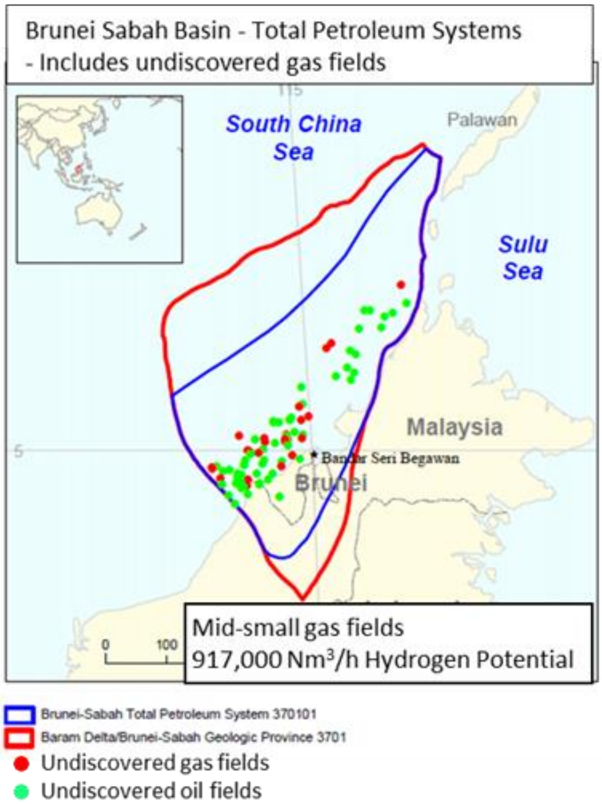


CCS = carbon capture and storage, EOR = enhanced oil recovery, T = tonne.
Source: Author (2020).

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

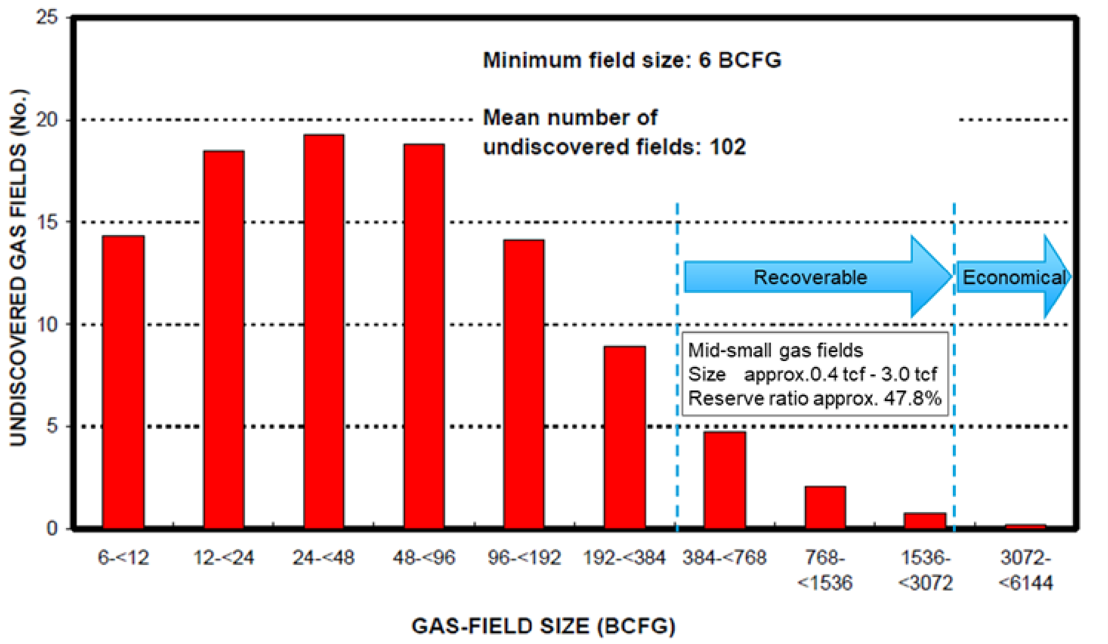


Source: USGS (2000).

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.

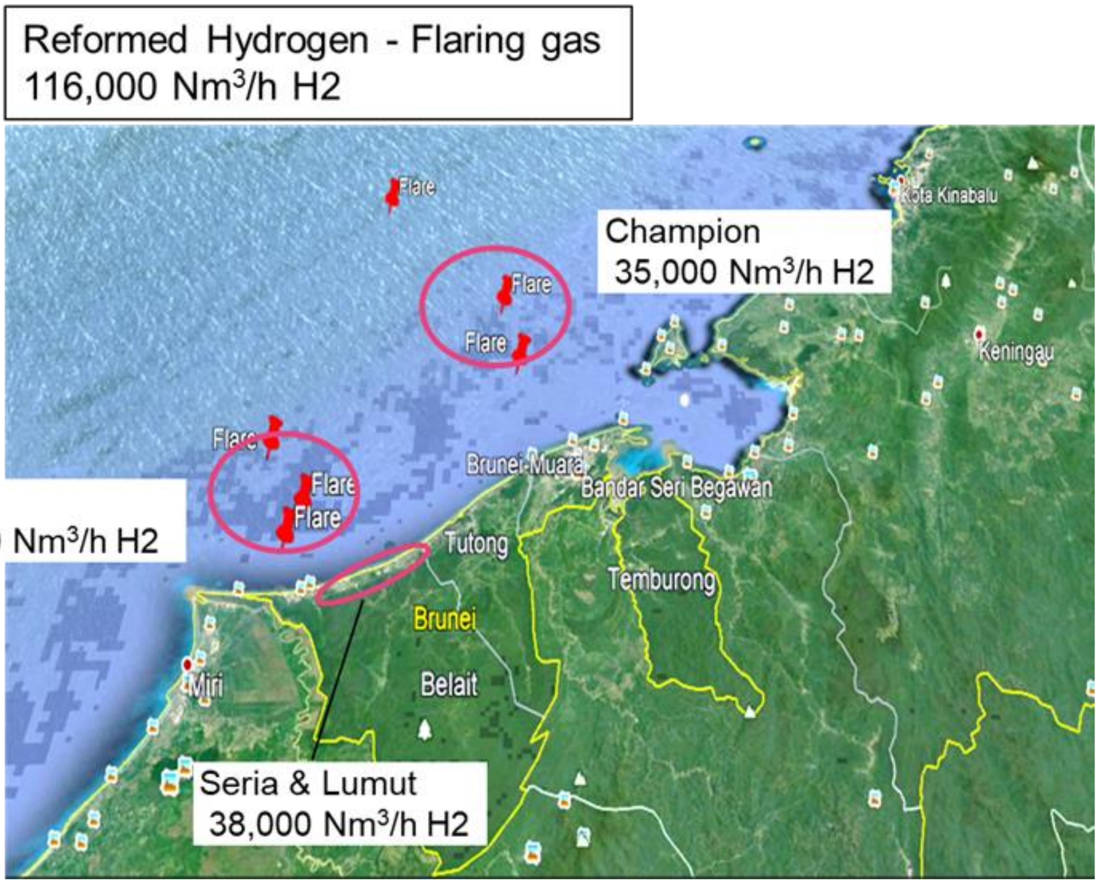
Figure 3.5: Brunei–Sabah Basin Undiscovered Gas Fields



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.

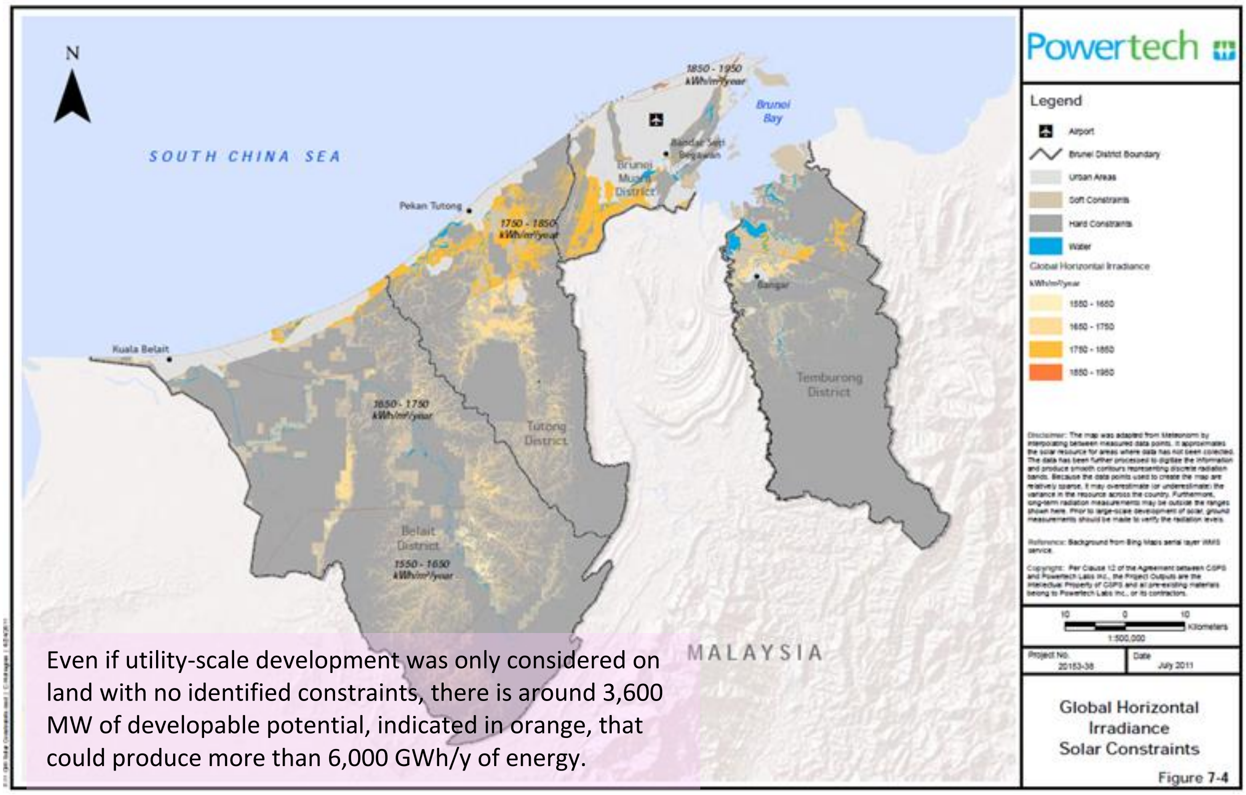
3.2.2. Potential of producing hydrogen from renewable energy

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).

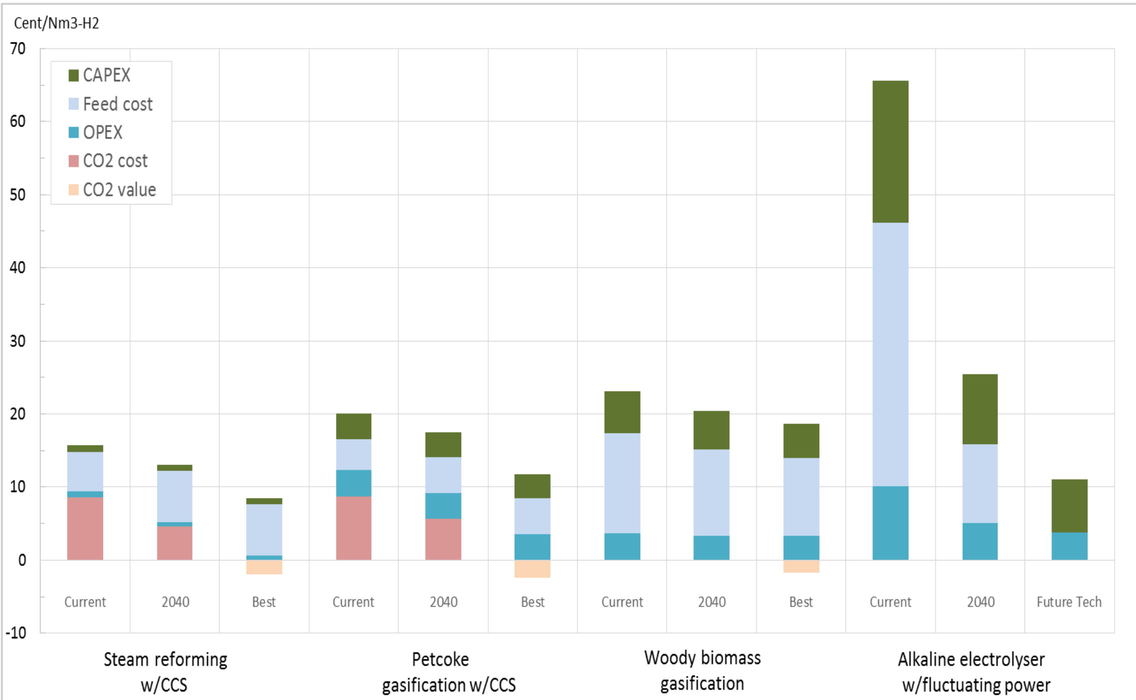
b. An example of hydrogen production cost

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

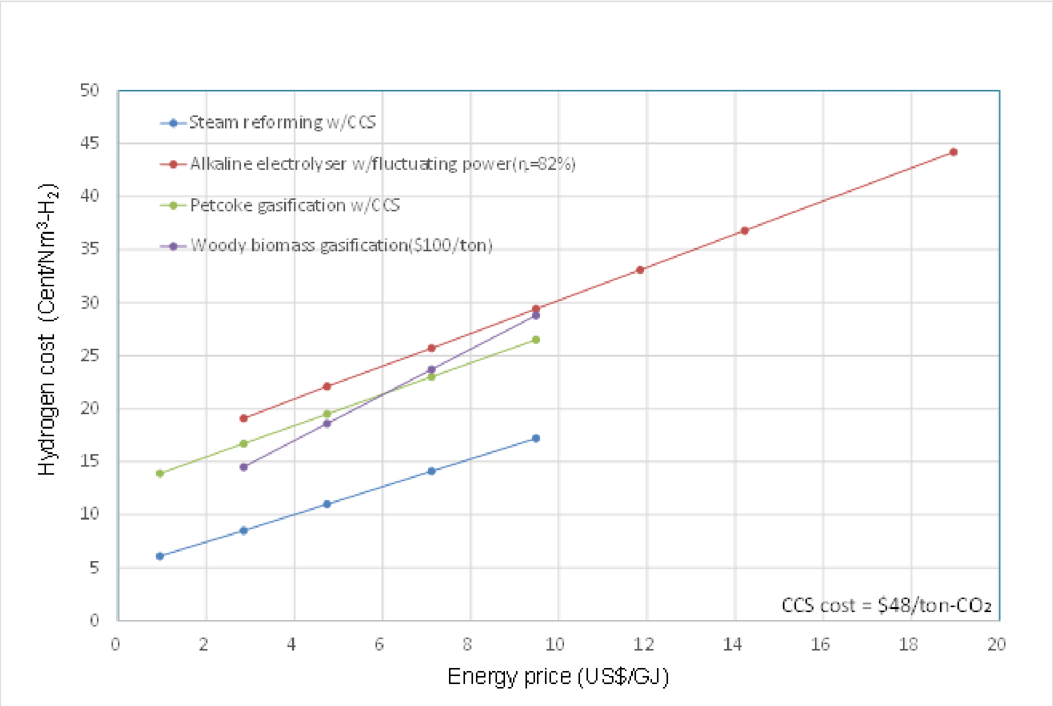


CCS = carbon capture and storage.
Source: Author (2020).

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



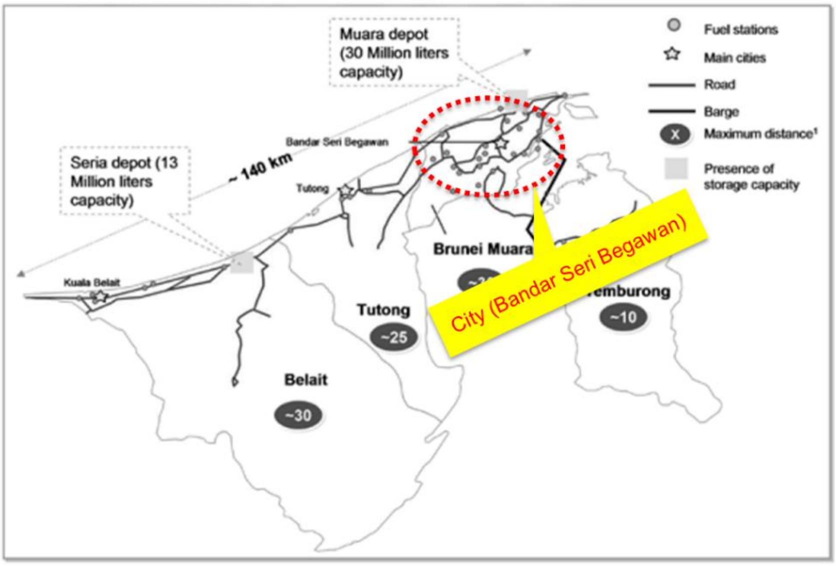
CCS = carbon capture and storage.
Source: Author (2020).

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).

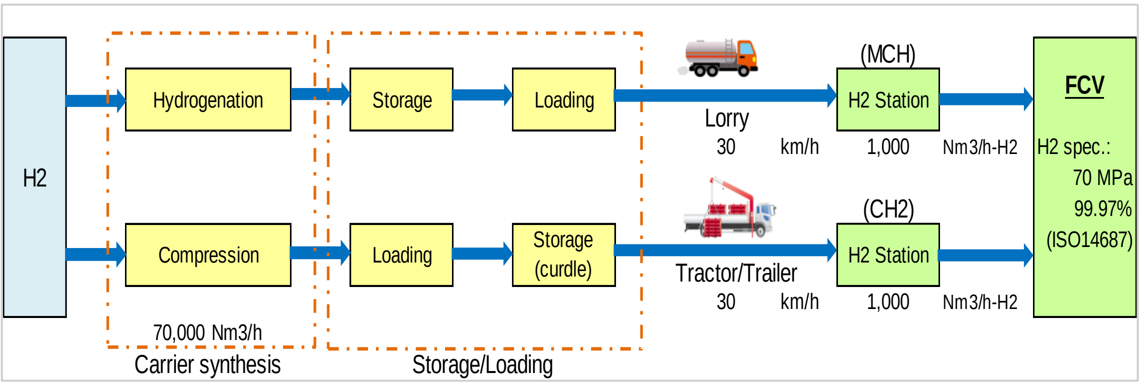
b. Comparison of transport costs between liquid organic chemical hydride and compressed hydrogen

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)

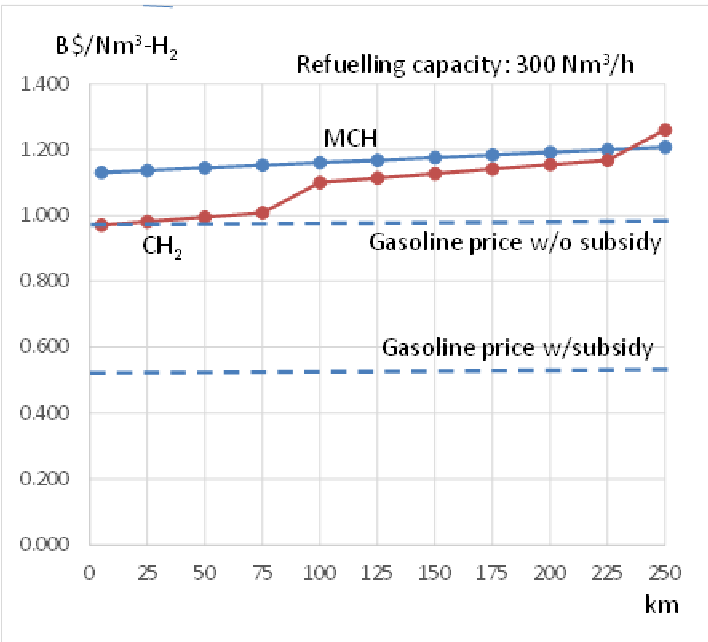


CH_2 = compressed hydrogen, FCV = fuel cell vehicle, MCH = methylcyclohexane.
Source: Author (2020).

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.

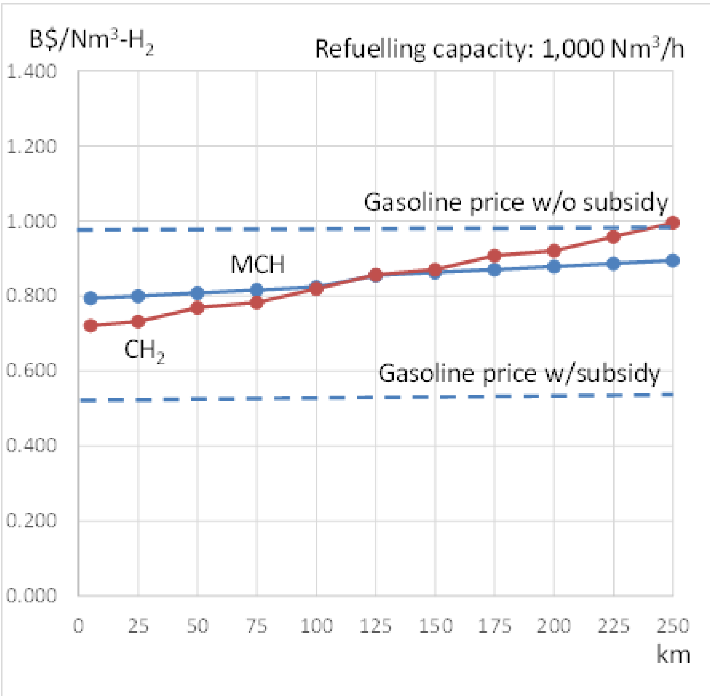
Figure 3.13 shows that up to 230 km, MCH has a higher transport cost than CH_2, and both hydrogen refuelling cost will be higher than gasoline price without subsidy. However, in the case of 1,000 Nm3/h of refuelling capacity, hydrogen refuelling cost will be less than gasoline price without subsidy at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

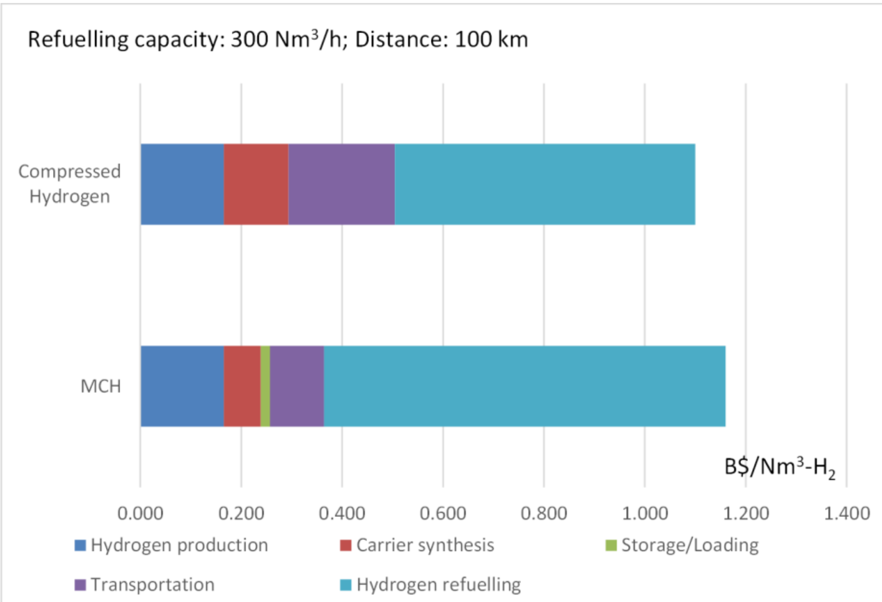
Figures 3.15 and 3.16 compare the component elements of transport cost between MCH and CH_2 at 100 km.

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.

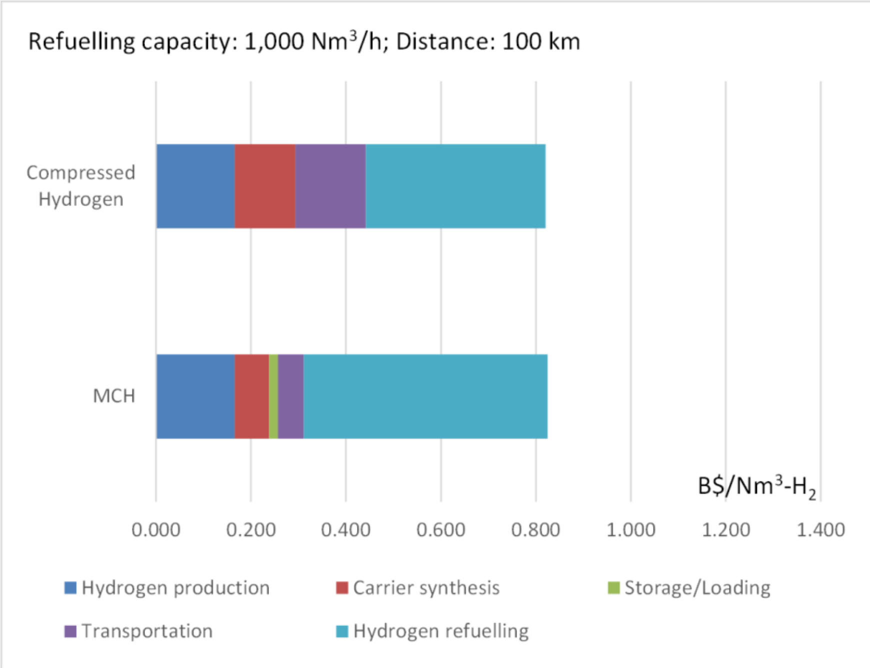
This is because MCH can transport around four times more hydrogen per shuttle compared to CH_2 transportation; in addition, MCH, which is in a liquid state, is easy to handle at ambient conditions and consequently can utilise existing infrastructures similar to the transport of petroleum products.

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)

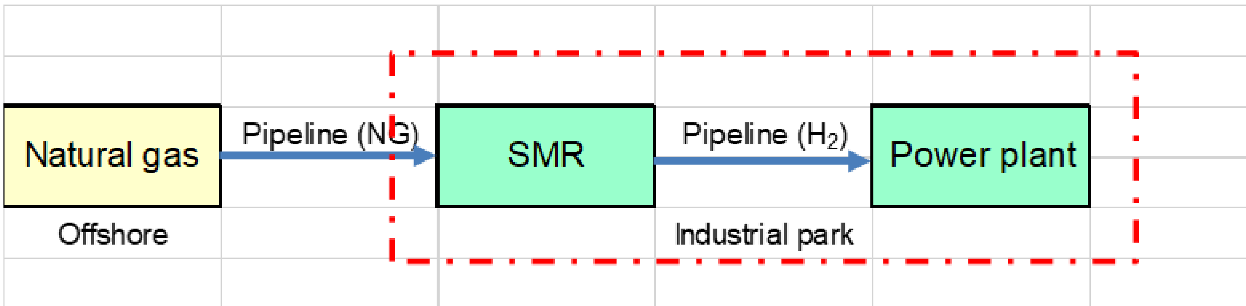


Source: Author (2020).

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).

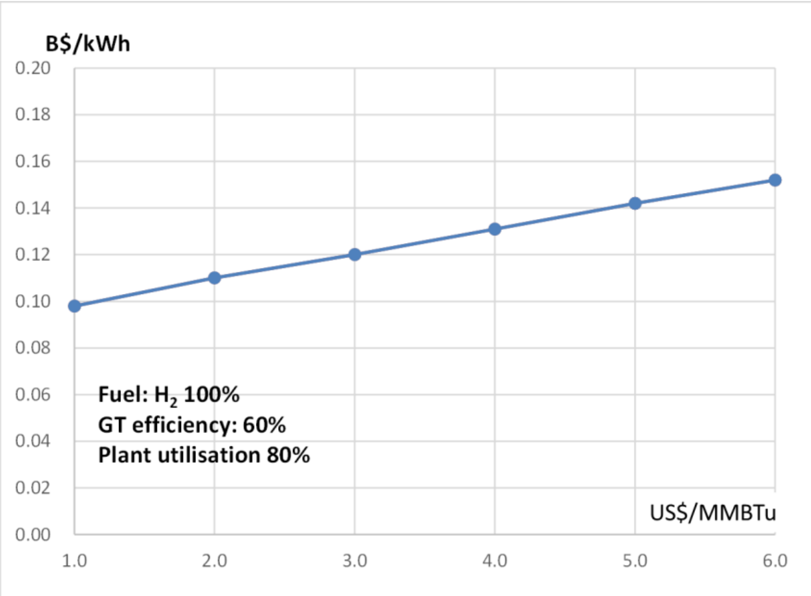
Figure 3.18 shows the correlation between electricity generation cost and natural gas price. The electricity cost estimation is based on hydrogen volume of 600,000 Nm^3/h, which is equivalent to half of the estimated power generation demand (1,252 ktoe per year) of Brunei in 2040.

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).

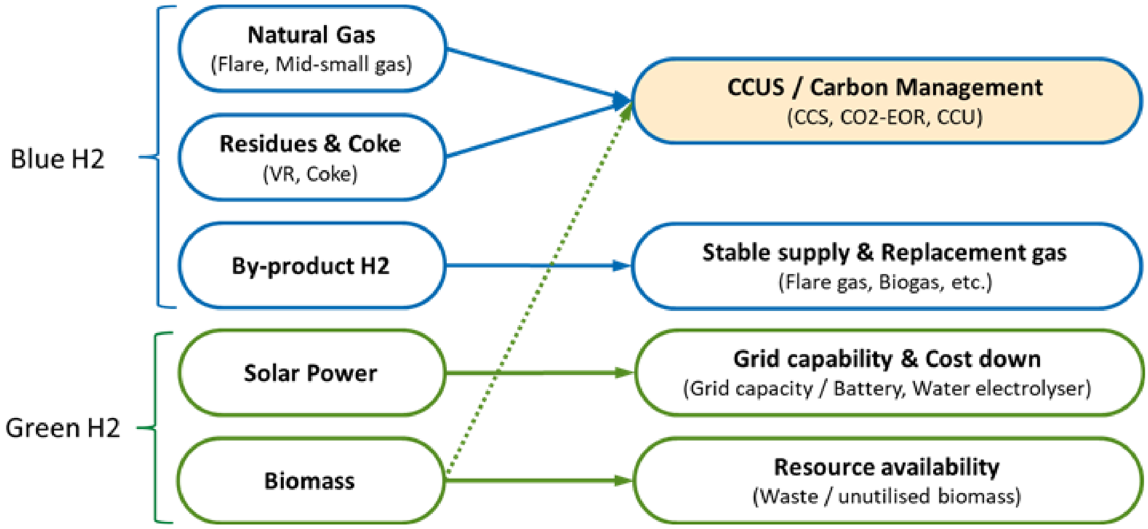
3.4. CO_2 Management

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



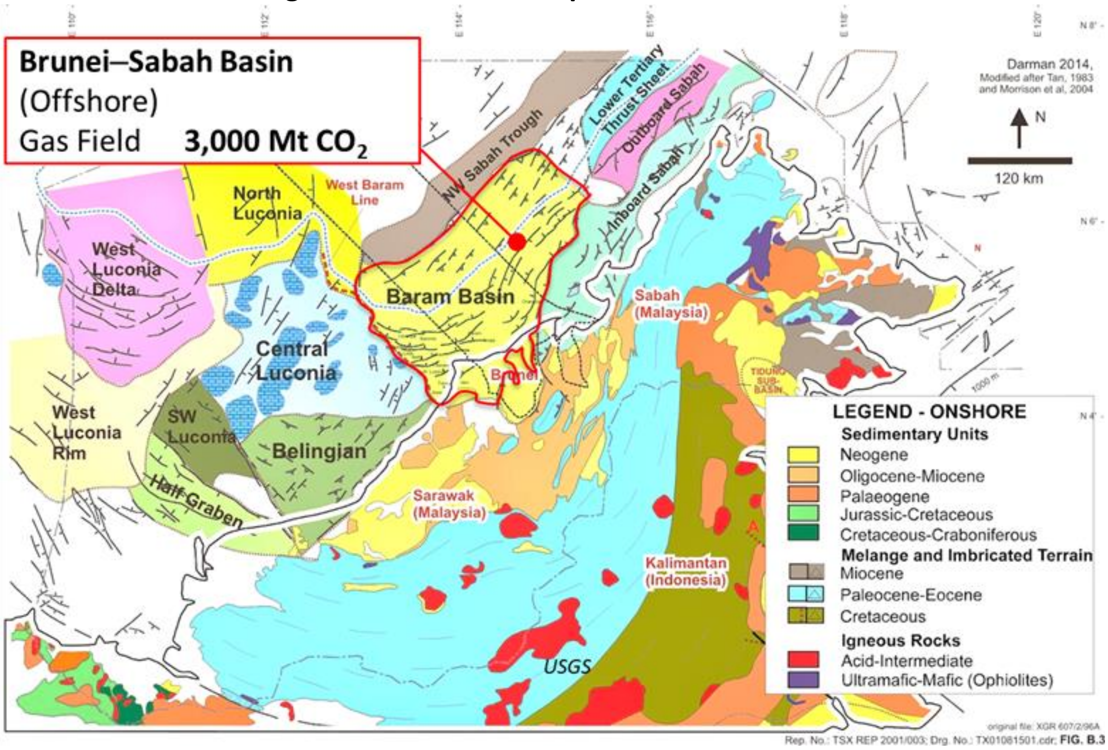
CCU = carbon capture and utilisation, CCUS = carbon capture utilization and storage, CO_2-EOR = carbon dioxide enhanced oil recovery, VR = vacuum residue.
Source: Author (2020).

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.

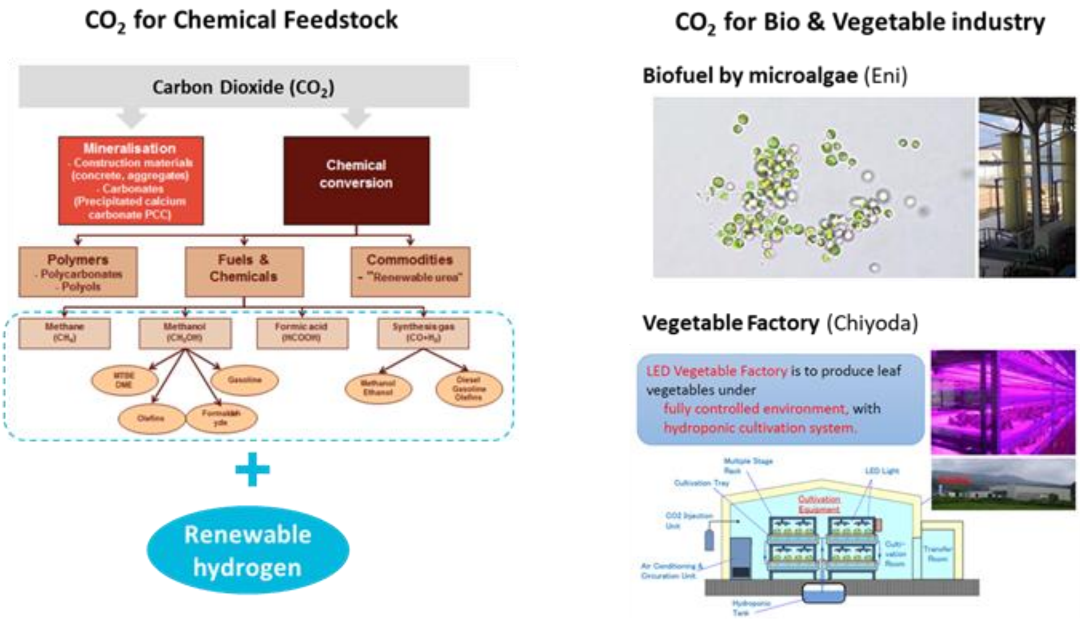
For example, CO_2 can be used as a chemical feedstock in certain chemical production processes by mineralisation or chemical conversions for polymers, fuels, including methane, methanol, formic acid, and synthetic gases and so on (SAPEA, 2018).

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).