ERIA Research Project Report FY 2023, No. 12

Study on Green Hydrogen Production in Brunei Darussalam

Department of Energy, Prime Minister's Office, Brunei Darussalam
With Support from
Economic Research Institute for ASEAN and East Asia

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Preface

Brunei Darussalam is famous for producing oil and natural gas, which are mainly exported to neighbouring countries as well as Japan and the Republic of Korea. Natural gas is defined as a transition fuel, such as coal to gas currently, and thus Brunei will be able to produce and export natural gas continuously in the coming decades. However, natural gas emits carbon dioxide (CO_2) amounting to half that of coal, so after 2040, gas will be phased out of the energy market in Asia due to the region becoming carbon neutral. In this regard, hydrogen is now being highlighted as a combustible fuel like natural gas, but which has no CO_2 emissions.

There are two types of hydrogen, blue hydrogen and green hydrogen. Blue hydrogen is produced from fossil fuels, such as coal and gas, with carbon capture and storage to reduce CO_2 emissions. On the other hand, green hydrogen is produced by applying electrolysis technology using electricity from renewable power sources, such as solar photovoltaic (PV). Brunei is rich in natural gas resources so it can produce lots of blue hydrogen. However, the country has limited renewable energy resources, and only solar PV is available for producing green hydrogen by applying electrolysis technology. Nonetheless, Brunei pays attention to the maintenance of its green areas (tropical rain forests), and whilst potential areas to set up solar PV are limited, they include bare ground without trees, reservoirs, rivers, and the sea in Brunei Bay. Consequently, floating type solar PV can be expected to be installed in the country. Based on electricity generation by solar PV systems, this project forecasts the potential production of green hydrogen in Brunei. Comparing hydrogen demand both inside and outside the country, green hydrogen production will be insufficient, and thus blue hydrogen will also be needed. Hydrogen will be a strategic fuel, similar to natural gas, and this report provides thoughts on hydrogen production policies in Brunei.

Shigeru Kimura
Special Advisor to the President on Energy Affairs
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Special acknowledgement is also given to Mr. Awang Haji Mohd Zaki bin Haji Hassanol As'Shari, Director of the Energy Stakeholders' Management Division, Department of Energy, Prime Minister's Office, Brunei Darussalam, and Mr. Shigeru Kimura, Special Advisor to the President on Energy Affairs, ERIA, for their excellent leadership of this project.

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List of Abbreviations and Acronyms

AC	Alternating Current
AEM	Anion Exchange Membrane
ALK	Alkaline Electrolyser
AMS	ASEAN Member State
APEC	Asia-Pacific Economic Cooperation
APS	Alternative Policy Scenario
ASEAN	Association of Southeast Asian Nations
BAU	Business as Usual
BEV	Battery Electric Vehicle
BFI	Brunei Fertilizer Industry
CCS	Carbon Capture Storage
CECEP	China Energy Conservation and Environmental Protection
CO_2	Carbon Dioxide
CR	Carbon Recycling
DC	Direct Current
DNV	Det Norske Veritas
DOE	Department of Energy
EAS	East Asia Summit
EE	Energy Efficiency
ESMAP	Energy Sector Management Assistance Program
EV	Electric Vehicle
FC	Fuel Cell
FCEV	Fuel Cell Electric Vehicle
FSPV	Floating Solar PV
GCL	Golden Concord Ltd.
GDP	Gross Domestic Product
GJ	Gigajoule
GW	Gigawatt

GWh	Gigawatt Hour
H_2	Hydrogen
Ha	Hectare
INDC	Intended Nationally Determined Contribution
IRENA	International Renewable Energy Agency
Ktoe	Kilotonnes of Oil Equivalent
Ktpa	Kilotonnes per Annum
KW	Kilowatt
KWh	Kilowatt Hour
MJ	Megajoule
MT	Megatonnes
MWe	Megawatt Electricity
MWh	Megawatt Hour
MWp	Megawatt Peak
NDC	Nationally Determined Contribution
NEL	National Energy Laboratory
Nm^3	Normal Cubic Metre
PEM	Polymer Electrolyte Membrane
PP	Power Plant
PV	Photovoltaic
RE	Renewable Energy
SERIS	Solar Energy Research Institute of Singapore
SOEC	Solid Oxide Electrolyser Cell
STEPS	Stated Policies Scenario
TW	Terawatt
UK	United Kingdom
US	United States
W	Watt

Executive Summary

Brunei Darussalam is rich in oil and gas production, but for renewable energy, only solar photovoltaic (PV) is available due to the strong sunshine. The land area of Brunei is physically and environmentally limited for setting up solar PV systems, but potential areas comprise bare ground, reservoirs, rivers, lakes, and Brunei Bay. According to this study, a total capacity of 1,030 megawatts (MW) of floating solar PV (FSPV) is available to be set up at reservoirs, rivers, and lakes in Brunei. In addition, a total of 700 MW of FSPV is available in Brunei Bay and a total of 424 MW of solar PV is available using bare ground. Thus, the total installed capacity for solar PV systems is estimated to be 2,154 MW in the country. If we assume a 17 % capacity factor for land-based solar PV systems and 19% for FSPV, the total power generation by solar PV systems is estimated at 3,510 GWh per year. If we assume a unit capital cost of solar PV and FSPV of US$800 per KW, the power generation cost is estimated at about US$0.0624 per kWh. When we use 3,510 GWh at the electrolyser facilities for producing hydrogen, the amount is estimated at 65.7 kilotonnes per year applying polymer electrolyte membrane (PEM) technology, and its hydrogen production efficiency is assumed at 4.77 kWh/Nm^3-H_2. If we assume a unit capital cost of the electrolyser facilities of US$1,050 per KWe, the total capital cost of the electrolyser is estimated at US$429 million, and the hydrogen production cost is also estimated as US$4.258 per kg-$H_2$.

Hydrogen combusts like fossil fuels but does not emit carbon dioxide, so hydrogen can be substituted for oil and gas consumption across sectors. Currently, oil and gas are largely consumed in the final energy consumption sector, which consists of the industry, transport, residential and commercial, and power generation sectors. According to this study, hydrogen demand for the power generation sector in the Association of Southeast Asian Nations (ASEAN) region is forecasted at 70 million tonnes, 1.3 million tonnes for the road transport sector, and 11.3 million tonnes for the industry sector in 2050. So far, hydrogen has not been used for energy, so a scenario approach is applied: 10% in 2030, 50% in 2040, and 100% in 2050 as the hydrogen cofiring ratio at gas power plants, and 30% in 2050 as the FCEV ratio to the total vehicle stock and the replacement of fossil fuels consumed for heat demand, such as for boilers and furnaces in the industry sector. As a result, green hydrogen production in Brunei is estimated at 73.4 kilotonnes per year. On the other hand, hydrogen demand in the ASEAN region, including Brunei, is forecasted to be more than 80 million tonnes per year by 2050. Thus, the amount of green hydrogen will not be able to meet hydrogen demand, so blue hydrogen produced from natural gas with carbon capture and storage will still be an important option for Brunei.

The investment amount for solar PV systems, mainly FSPV and water electrolysis, is estimated at about US$2,152 million and is significant compared to the annual gross fixed capital formation of about US$5,000 million. Thus, Brunei can expect a large economic impact with the operation of both facilities. However, there is still an issue of the higher green hydrogen production cost at US$3.5–US$5.2/kg-H_2 according to this study. The global target of the hydrogen supply cost will be US$1–US$2/kg-H_2, thus we need to investigate measures for hydrogen supply cost reduction, such as further cost reductions in solar PV systems and improvements in hydrogen production efficiency by applying electrolysis technology. If Brunei exports 5 million tonnes of hydrogen, including blue hydrogen, this will amount to around US$10 billion, almost the same as the export value for Brunei in 2019. Thus, the production of blue hydrogen is indispensable for Brunei.

In addition, Brunei will be able to impot electricity from Sarawak province, Malaysia, which will be generated by hydropower plants. If Brunei imports 1GW electricity from Sarawak province, Brunei can produce green hydrogen around 65 kiloton/year, if we assume capacity factor of the hydropower at 40%. It is significant and electricity import from Sarawak province will be a very important option for Brunei to increase green hydrogen production.

Chapter 1
Introduction

Hydrogen is a promising fuel and technology for becoming carbon neutral towards 2050 or 2060, and Brunei Darussalam has significant potential for producing blue and green hydrogen. Blue hydrogen is produced from natural gas or as a by-product of the liquefied natural gas production process. Green hydrogen is produced from electrolysis facilities using electricity from renewable energy, such as hydropower, geothermal power, biomass, solar, and wind. However, Brunei only has solar photovoltaic (PV) potential due to its geographical and climate conditions.

Thus, this project firstly surveys solar PV potential capacity in Brunei, focusing on water surfaces and the bare ground. When we conduct the survey on land, we need to pay attention to forest areas. Secondly, based on the solar PV potential capacity and assumed capacity factor of the solar PV system, the amount of electricity generation by the solar PV system is estimated. Thirdly, this project estimates hydrogen production amounts based on the power generation by the solar PV system referring to existing hydrogen production efficiencies, such as the International Renewable Energy Agency (IRENA).

This project also forecasts hydrogen demand by 2040 in and out of Brunei by sector – power, industry, and transport. The export targets of Brunei are other Association of Southeast Asian Nations (ASEAN) countries, such as Indonesia, Malaysia, the Philippines, Singapore, and Thailand. If green hydrogen production does not meet the hydrogen demand in the ASEAN region, Brunei will need to produce blue hydrogen to supply to the ASEAN countries.

In addition, this project studies economic analysis of the green hydrogen business for Brunei. This study focuses on a review of oil and gas historical production, estimation of capital investment of the solar PV system and electrolyser facilities, the economic impact of the capital investment on Brunei's economy, and the possibility of clean hydrogen for replacing oil and gas exports. Not only Brunei Darussalam but also other countries, such as Middle Eastern countries, India, and Australia, will produce clean hydrogen and export it to Asian countries, so Brunei will face hard competition regarding exports of clean hydrogen. One advantage for Brunei Darussalam is its location, as it is closer to ASEAN and East Asian countries than Middle Eastern countries, India, and Australia. Thus, Brunei will play a key role in the clean hydrogen supply network in the East Asia Summit region.

Chapter 2
Forecast for Potential Solar PV Capacity in Brunei Darussalam

1. Examples of Floating Solar PV Systems

The following are examples of existing floating solar PV (FSPV) systems:

- Yamakura Floating Solar Power Generation Station, Chiba Prefecture, Japan
- Singapore's floating solar farm on the Tengeh Reservoir
- Woodlands, Straits of Johor

(1) Yamakura Floating Solar Power Generation Station, Chiba Prefecture, Japan, 2018

- Polycrystal silicon panel : 305 watts (W)/panel x 44,898 = 13.7 megawatts electric (Mwe) (11.5 MWe transmitted)
- Annual output : 16,100,000 kilowatt-hours (kWh) (capacity factor 16 %)
- Surface area : 18 hectares (ha) (water surface area: 61 ha)

Figure 2.1. Yamakura Floating Solar Power Generation Station, Chiba Prefecture, Japan

Source: News release of Kyocera, 1 October 2021.

Kyocera's 13.7 MWe floating solar panels were damaged by 200 kilometres per hour (km/h) winds that Typhoon Faxai brought to the coastal city of Chiba in 2019. After around 2 years of remedial work, the FSPV system restarted operations in 2021 with six separated solar panel islands as shown in Figure 2.1.

(2) Singapore’s floating solar farm on the Tengeh Reservoir, 2021

- Made up of 122,000 solar panels spanning 45 ha
- Solar panels spread across 10 solar panel islands
- 60 megawatt (MW) peak solar PV ⇒ 60,000/122 = 490 W/panel

Figure 2.2. Tengeh Floating Solar Farm in Singapore

Source: Singapore International Water Week (n.d.) Sembcorp Tengeh Floating Solar Farm. https://www.siww.com.sg/spotlight-2023/programme/technical-site-visits/sembcorp-tengeh-floating-solar-farm

The solar farm was deployed as part of Singapore's goal to quadruple solar energy capabilities by 2025. The farm is designed, built, owned and operated by Sembcorp Floating Solar Singapore in partnership with the Public Utilities Board, which regulates and oversees the water supply system in Singapore.

(3) Woodlands, Straits of Johor, 2021

- Power generation : 5 MWe
- Configuration of farm : 13,312 panels, 40 inverters and >30,000 floats
- Annual output : 6,000 MWh (capacity factor 14 %)

The solar farm consists of electrical panels, a control system, 22-kilovolt (kV) transformers, and a landing point for the subsea cable transmitting generated power to the national grid. The floating PV system is designed with a robust constant tension mooring system.

Figure 2.3. Offshore Floating Solar Farm in Johor, Malaysia

Source: Hill, J. (2021), Sunseap Completes Offshore Floating Solar Farm in Straits of Johor. https://reneweconomy.com.au/sunseap-completes-offshore-floating-solar-farm-in-straits-of-johor/

2. Current State and Plans for Global FSPV Installation

Table 2.1 shows the current construction records and plans for FSPVs of 5 megawatt-peaks (MWp) or more. The largest of these is planned for Madhya Pradesh in India, which is expected to start generating 600 MWp in 2022–2023.

China accounts for the majority of FSPVs of 100 MWp or more, and these are characterised by the fact that FSPVs are installed in ponds made from abandoned mines.

As can be seen from Table 2.1, FSPVs are mainly installed in inland water bodies. This is because the environmental load given to the floating structure is much more severe in seas than in inland waters.

As for offshore FSPV, in addition to the 5 MWp installed in the Straits of Johor, a small offshore unit called SolarSea has been introduced in the Maldives. The unit is said to be able to withstand waves of up to 1.5 m high and winds of 10 km/h, as well as strong ultraviolet and humidity.

In Japan, there are no FSPVs installed on the sea yet, but a demonstration test of floating solar power generation is planned as the Tokyo Bay eSG project, with an implementation period from 2022 to 2024. The details of the implementation procedure are as follows.

- Design and installation of multiple floating systems
- Design and installation of floating structures and mooring systems for offshore use
- Verification of the effects of salt damage on electrical equipment
- Comparative verification of the power generation number of different types of floating systems, such as offshore and onshore

Table 2.1. Current State and Plans for Global FSPV Installation

Category	Size (kWp)	Water Body and Nearest City	Country	City/Province	Floating System Supplier(s) (and subcontractor, if possible)	Completion Year
L&D	600,000	Madhya Pradesh, reservoir formed by the Omkareshwar Dam	India	Khandwa District	-	2023
L&D	320,000	Dezhou Dingzhuang Floating Solar Farm reservoir in Shandong	China	Dezhou	Beijing Electric Company Huaneng Power International	2022
MS	150,000	Coal mining subsidence area, Huainan City (Fengtai Guqiao-Sungrow)	China	Anhui Province	Beijing NorttMan, Zhongya, Hefei Jintech New Energy Co. Ltd., Anhui ZNZC New Energy Co. Ltd., CJ Institute China	2018
MS	150,000	Coal mining subsidence area, Huainan City (Panji-China Three Gorges New Energy)	China	Anhui Province	Sungrow Floating (Anhui ZNZC New Energy Technology Co. Ltd.)	2018
MS	130,000	Yingshang coal mining subsidence area, (Liuzhuang mine-Trina Solar)	China	Anhui Province	Anhui ZNZC New Energy Technology Co. Ltd., Shanghai Qihua Wharf Engineering Co. Ltd., etc.	2018
MS	102,000	Coal mining subsidence area, Huainan City (Fengtai Xinji)	China	Anhui Province	Sungrow Floating (Anhui ZNZC New Energy Technology Co. Ltd)	2017
MS	100,000	Coal mining subsidence area, Jining City	China	Shandong Province	Sungrow Floating	2018
L&D	70,005	Mine Lake, near Huaibei (CECEP)	China	Anhui Province	Ciel & Terre International	2018
L&D	60,000	Tengeh Reservoir, Southwest, Singapore	Singapore	-	Sembcorp Industries	2021
MS	50,000	Coal mining subsidence area, Jining City (Shandon Weishan)	China	Shandong Province	Sungrow Floating	2017
L&D	45,000	Sirindhorn dam, Ubon Ratchathani	Thailand	-	-	2021
MS	40,000	Renlou coal mine in Haibei City (Trina Solar)	China	Anhui Province	Shanghai Qihua Wharf Engineering Co. Ltd., etc.	2017
MS	40,000	Coal mining subsidence area, Huainan City (20+20 Panji)	China	Anhui Province	Sungrow Floating	2017

Table 2.1. Current State and Plans for Global FSPV Installation (continued)

Category	Size (kWp)	Water body and nearest city	Country	City/Province	Floating system supplier(s) (and subcontractor, if possible)	Completion year
L&D	32,686	Mine Lake (Golden Concord Ltd (GCL)	China	Anhui Province	Ciel & Terre International	2018
MS	31,000	Coal mining subsidence area, Jining City (Shandong Weishan)	China	Shandong Province	Sungrow Floating	2017
MS	20,000	Coal mining subsidence area, Huainan City (Xinyil)	China	Anhui province	N/A	2016
L&D	18,700	Gunsan Retarding Basin	Korea, Rep of	North Jeolla	Scotra Co. Ltd.	2018
L&D	13,744	Yamakura Dam Reservoir	Japan	Chiba	Ciel & Terre International	Original 2018, modification 2021
-	10,982	Xuzhou Pei Country	China	Jiangsu Province	Ciel & Terre International	2017
L&D	9,087	Urayasu Ike	Japan	Chiba	Ciel & Terre International	2018
-	8,500	Wuhu, Sanshan	China	Anhui Province	N/A	2015
L&D	8,000	Lake in Xingtai, Linxi Country	China	Hebei	N/A	2015
L&D	7,550	Umenoki Irrigation Reservoir	Japan	Saitama	Ciel & Terre International	2015
L&D	6,800	Hiritani Ike	Japan	Hyogo	Takiron Engineering Co. Ltd.	2018
L&D	6,776	Amine Lake, Jining City	China	Shandong Province	Ciel & Terre International	2015
L&D	6,338	Queen Elizabeth II Drinking Water Reservoir	United Kingdom	London	Ciel & Terre International	2016
SEA	5,000	Straits of Johor	Singapore	-	Sunseap Group	2021

KWp = kilowatt peak, L&D: lake, dam, and water reservoir, MS = mining subsidence, SEA = sea area.
Source: World Bank Group, ESMAP, and SERIS (2019), *Floating Solar Market Report*; various websites.

3. Pros and Cons of FSPV

FSPV systems have different pros and cons from the points of view of design, installation, and operation. The pros and Cons of FSPV systems are listed below.

- Pros of FSPV:
  (1) Shortened construction period as no need for deforestation or ground preparation.
  (2) Maintaining forests and preserving limited land for other purposes, such as industrial needs.
  (3) The cooling effect of water leads to higher power generation efficiency compared to ground-mounted solar PV systems.
  (4) The shading effect of the panels helps to reduce evaporation and the presence of algae blooms in water.

- Cons of FSPV:
  (1) Onboard work and underwater work are necessary to install panels and structures.
  (2) The cost of building FSPVs is more expensive than ground-mounted solar PV, due to the need to build floating structures.
  (3) Shading effect of the panels leads to an increase in phytoplankton and, as a result, water degradation.
  (4) Necessity of FSPV system design that does not spoil the scenery.

4. Suitable Area for FSPV Installation

A suitable area for installing an FSPV system on the water surface has to fulfil the following conditions:

- High solar radiation: Brunei 4.00–4.99 kWh/m^2/day
- Environment
  (1) No shading effect on FSPV modules
  (2) Water depth: < 10 m
  (3) Stable water surface
  (4) Normal wind speed: < 34 m/s
  (5) Few water-level fluctuations
  (6) No severe weather conditions
- Grid connection
  (1) Connecting facility can be easily installed nearby
  (2) Underwater or floating cable connection to the facility

5. Candidate Sites for PV in Brunei

Table 2.2 and Figure 2.4 show the candidate sites for floating PV and ground-mounted PV.

Table 2.2. Candidate Sites for PV in Brunei Darussalam

Category	Site	Estimated Area (ha)	Estimated Capacity (MW)	Source
	Mengkubau Dam	197	125	(1)
	Benutan Dam	639	406	(1)
	Ulu Tutong Dam	517	329	(1)
	Kargu Dam	286	170	(2)
Brunei Bay	Serasa Bay	47	30	(3)
	Both sides of Temburong Bridge	1,000	640	(3)
	Muara Besar Island	47	30	(3)
Ground-mounted	Kg Belimbing	38	38	(1)
	Sungai Teraban	202	200	(1)
	Bukit Panggal	50	62	(2)
	Kg Tanjung Bungar	12	15	(2)
	Kg Seri Tanjung Belayang	50	62	(2)
	Kg Belingus	38.5	47	(2)

Ha = hectare, MW = megawatt.
Sources:
(1) ‘Potential Sites for Solar Installation in Brunei Darussalam Nov 2022 Department of Energy’, presented at 1st Working Meeting on the Green Hydrogen Production in Brunei Darussalam, 28 November 2022.
(2) Communications with the Department of Energy, Prime Minister’s Office, Brunei Darussalam.
(3) 1st Working Meeting on the Green Hydrogen Production in Brunei Darussalam, 28 November 2022, and subsequent study.

Figure 2.4. Candidate Sites for PV in Brunei Darussalam

Source: Authors.

6. Capacity Factor in Brunei

6.1. Capacity Factor of FSPV

FSPV is said to have a 5%–10% increase in power generation efficiency compared to ground-mounted PV, as the panel temperature rise is suppressed by the cooling effect of the water. For this reason, when setting the capacity factor of FSPV to be installed in Brunei, we referred to Japan's Toyoake floating mega-solar power plant, for which the operating data have been published.

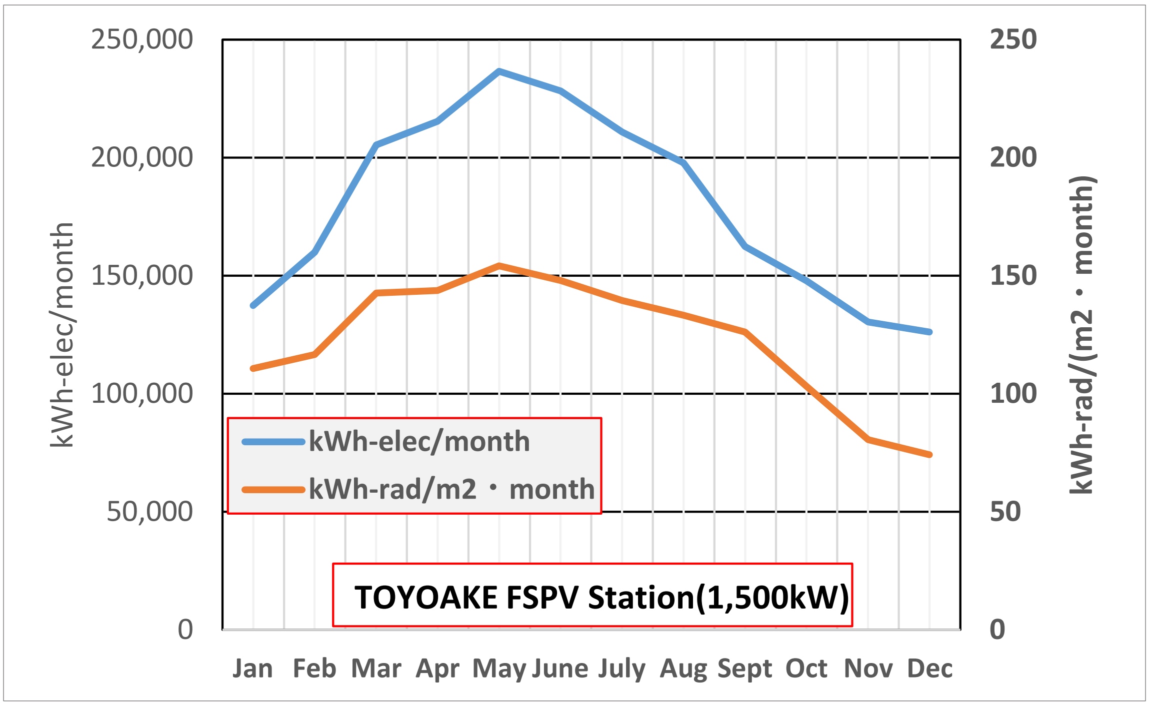
(1) Outline of Toyoake FSPV

- Location : Aichi Prefecture, Japan
- Installed Capacity : 1,500 kWp
- Area/panel : 1.9 ha/6,720 panels
- Operation : Since March 2017 (data for 2022 are shown in Figure 2.6)

Figure 2.5. Toyoake Floating Mega Solar Power Plant

Source: Toyoake City Office (n.d.). https://www.city.toyoake.lg.jp/4558.htm

Figure 2.6. Operational Data for Toyoake FSPV, 2022



Source: Authors.

(2) Comparison of climatic data on Brunei and Toyoake

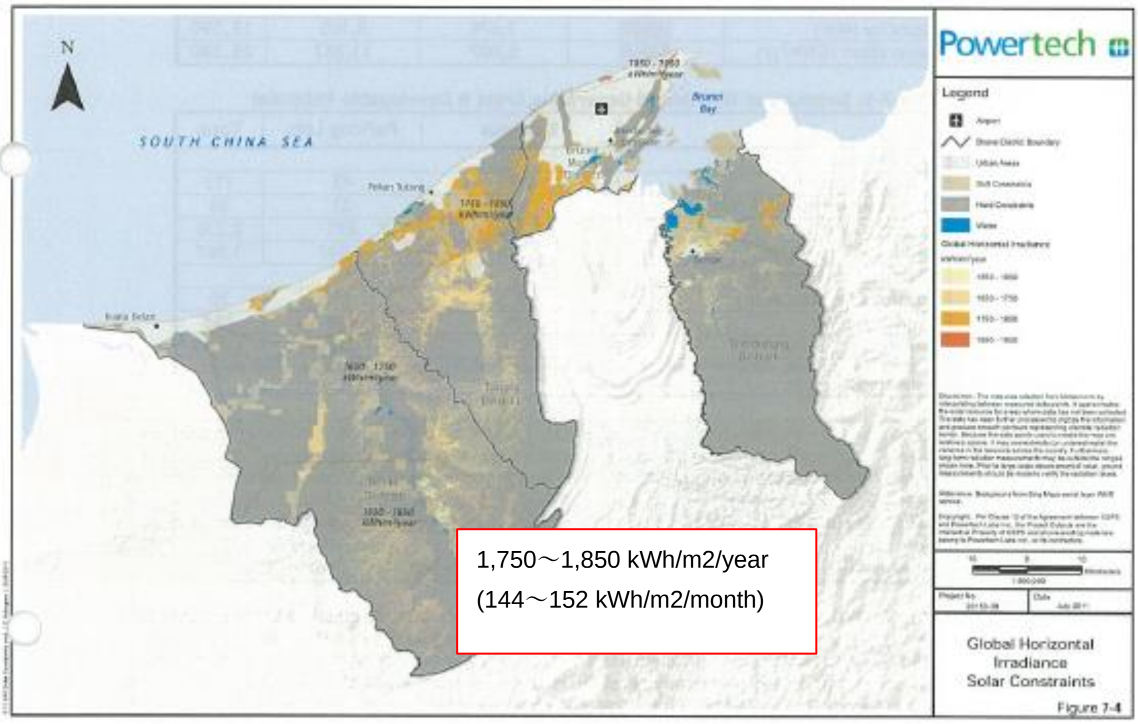
Table 2.3 shows data on temperature, humidity, precipitation, and solar irradiance for Brunei and Toyoake. The irradiance levels in Brunei are shown in Figure 2.4.

Table 2.3. Comparison of Climatic Data for Brunei Darussalam and Toyoake

	May	June	July	August	September
Temperature (ºC)					
Brunei Darussalam	28.8	28.7	28.0	27.9	28.4
Toyoake	118.4	22.3	26.0	27.2	23.7
Humidity (%)					
Brunei Darussalam	78	77	79	78	76
Toyoake	72	78	81	77	77
Precipitation (mm)					
Brunei Darussalam	156.5	70.5	82.5	263.5	151.5
Toyoake	141	181	173	120	204
Solar Irradiance (kWh/m^2/month)					
Brunei Darussalam	144–152 (annual average)				
Toyoake	154	148	139	133	126

Source: Brunei Darussalam: Communications with Department of Energy, Prime Minister's Office, Brunei Darussalam; Toyoake City (https://www.city.toyoake.lg.jp/).

Figure 2.7. Irradiance Levels in Brunei Darussalam



Source: *Feasibility Study for Alternative Energy Sources for Brunei Darussalam, A Report to the Centre for Strategic and Policy Studies*, submitted by Powertech, Canada, 2011.

(3) Estimation of capacity factor of FSPV in Brunei

As shown in Table 2.3, Toyoake's climate conditions from May to September are similar to those of Brunei, so the actual values of Toyoake's capacity factor (shown in Table 2.4) are taken for the estimation for Brunei.

Table 2.4. Capacity Factor at Toyoake

	May	June	July	August	September
Capacity Factor (%)	21	21	19	18	15

Source: Authors.

Based on the above, the capacity factor of FSPV in Brunei was set at 19% by adopting the average value from May to September at Toyoake.

6.2. Capacity Factor of Ground-mounted Solar

Mordor Intelligence[1] has reported that Brunei has a large solar potential due to its geographical location, with over 90% of the country having a solar potential of 1,400–1.600 kWh/kWp/year.

From the figure of 1,400–1.600 kWh/kWp/year, a capacity factor of 16%–18% was derived for ground-mounted solar, and a capacity factor of 17% was set for ground-mounted solar.

[1] https://www.mordorintelligence.com/industry-reports/brunei-power-market

Chapter 3
Forecast for Potential Green Hydrogen Production in Brunei Darussalam

1. Electrolysis Technologies

An electrolyser consists of a number of cells connected together with common electric terminals, i.e., bus bars. Each cell is composed of two electrodes, two porous transport layers, and the bipolar plates. Other parts of the electrolyser system include transformers, rectifiers, and process units, such as for water treatment, gas cooling, gas scrubbing, hydrogen (H_2) deoxidising, H_2 drying, and gas compression/storage.

Four types of electrolysers are under focus: alkaline electrolyser (ALK), polymer electrolyte membrane (PEM), solid oxide electrolytic cell (SOEC), and anion exchange membrane (AEM). Amongst the four types, SOEC and AEM are still in the development stages, and ALK and PEM are well-commercialised. From the view of cost and availability, ALK is much superior to PEM, but from the view of flexibility for intermittent renewable energy, PEM is better than ALK.

Table 3.1 shows a comparison of the commercialised electrolysers.

Table 3.1. Comparison between ALK and PEM

	Alkaline Electrolysis (ALK)	**Polymer Electrolyte Membrane (PEM)**
Technology maturity	Well-commercialised	Commercialised
Product H_2 purity	>99.95% module outlet (dry gas basis)	>99.7% module outlet (dry gas basis)
Responsiveness/Ramp rates	4%/sec (0%–100% load)	10%/sec (0%–100% load)
Operating load range	10%–100%	20%–100%
Electricity Efficiency		
Stack DC (kWh/Nm^3-H_2)	3.8–4.6	3.8–4.4
Plant AC (kWh/Nm^3-H_2)	4.7–5.6	4.7–5.6
Vendors/original equipment manufacturers	NEL, Thyssenkrupp, Asahi Kasei, Suzhou Jungli	Siemens, NEL, ITM Power, Cummins

Source: Authors.

2. FSPV potential and hydrogen production in Brunei

Table 3.2 shows the estimated electricity capacity and electricity generation derived by using the capacity factors for inland, offshore, and ground-mounted PV. Also, H_2 production is estimated by using an electrolyser efficiency of 4.77 kWh/Nm^3-H_2.

Table 3.2. PV Potential and H_2 Production in Brunei Darussalam

Type	Area	Site		Catchment Area	Water Storage	Average Depth	Estimated Area for PV		Estimated Electricity Capacity		Capacity Factor	Electricity Generated	Estimated H_2 Production	Remarks
				(ha)	(million m^3)	(m)	(ha)	(% of catchment)	(MW)	(MW/ha)	(%)	(MWh/y)	(kilotonnes/y)	
Floating PV	Lake, dams, and reservoir	1	Tasek Dam	427	1.1	0.26	85	20	55	0.64	19	91,032	1.70	(*2)
		2	Mengkubau Dam	1,370	16.8	1.23	197	14.4	126	0.64	19	209,858	3.93	(*1)
		3	Benutan Dam	2,900	56	1.93	639	22.0	408	0.64	19	679,540	12.71	(*1)
		4	Ulu Tutong Dam	10,800	80	0.74	517	4.8	330	0.64	19	549,628	10.28	(*1)
		5	Kargu Dam	1,430	10.7	0.75	286	20	183	0.64	19	304,860	5.70	(*2)
		6	Kago Dam	-	-	-	267	-	171	0.64	19	284,607	5.32	(*1)
		7	Imang Reservoir	1,400	10	0.71	188	-	120	0.64	19	200,398	3.75	(*1)
								Subtotal	**1,393**			**2,319,924**	**43.40**	
	Brunei Bay	1	Serasa Bay	-	-	-	47	-	30	0.64	19	50,099	0.94	(*3)
		2	Both sides of Temburong Bridge	-	-	-	1,000	-	640	0.64	19	1,065,946	19.94	(*4)
		3	Muara Besar Island	-	-	-	47	-	30	0.64	19	50,099	0.94	(*3)
								Subtotal	**700**			**1,166,144**	**21.81**	
	Land-based	1	Sg Akar	-	-	-	38	-	38	1.00	17	56,628	1.06	(*1)
		2	Pekan Belait	-	-	-	56	-	56	1.00	17	83,452	1.56	(*1)

Type	Area	Site		Catchment Area	Water Storage	Average Depth	Estimated Area for PV		Estimated Electricity Capacity		Capacity Factor	Electricity Generated	Estimated H_2 Production	Remarks
				(ha)	(million m^3)	(m)	(ha)	(% of catchment)	(MW)	(MW/ha)	(%)	(MWh/y)	(kilotonnes/y)	
Ground-mounted PV		3	Sungai Teraban	-	-	-	202	-	200	0.99	17	298,044	5.58	(*1)
								Subtotal	**294**			**438,125**	**8.20**	
Grand total									**2,387**			**3,924,193**	**73.41**	

*1 The values of the estimated area for PV and estimated electricity capacity (MW) are used from the report 'DOE Potential Sites for Solar Installation in Brunei Darussalam, November 2022'.
*2 The values of the estimated area for PV are set to 20% of the catchment area, and the values of the estimated electricity capacity are calculated using 0.64 MW/ha.
*3 The maximum value of the FSPV installed in the sea area is 5 MW in the Johor Strait, Singapore, but in the study, it was set to 30 MW which is 6 times that.
*4 PV panels shall be installed in an area of 500 m in width and 10,000 m in length on both sides of the Temburong Bridge.
Source: Authors.

3. Calculation of Green Hydrogen Cost

The green hydrogen cost is calculated from the PV potential (estimated electricity capacity), which is summarised in Table 3.2 with the following procedure.

- Electricity generated
  - (1) PV potential : 2,154 MW
  - (2) Capacity factor of PV : 17% (land-based)–19% (water surface)
  - (3) Electricity generated : 3,510,832 MWh/y
  - (4) 1,730 MW x 8,760 hrs/y x 0.19 : 2,879,412 MWh/y (water surface)
  - (5) 424 MW x 8,760 hrs/y x 0.17 : 631,420 MWh/y (land-based)
- H_2 production
  - (1) PEM electricity efficiency : 4.77 kWh/Nm^3-H_2
  - (2) H_2 production:
    - a. 3,510,832 MWh/y / 4.77 kWh/Nm3 : 736 MNm^3/y
    - b. 736 MNm^3/y / 11.2 Nm^3/kg : 65.7 kilotonnes/y
- Calculation of green hydrogen cost

(1) Renewable electricity cost	: 0.05	0.07	US$/kWh
(2) Green hydrogen cost	: <u>3.5–4.1</u>	<u>4.6–5.2</u>	US$/kg-$H_2$

4. Conclusion

- Green hydrogen produced from electrolysis technologies using renewable electricity is an option for Brunei for achieving a low-carbon energy transition.
- The RE potential from FSPV systems of inland water surfaces in Brunei and Brunei Bay and from ground-mounted PV is estimated at 2,154 MWp.
- The electricity generation per year is calculated using capacity factors of 19% for water surface and 17 % for ground-mounted at 3,510,832 MWh/y.
- The above electricity generation gives 65.7 kilotonnes/y of hydrogen production using a PEM electrolyser with an efficiency of 4.77 kWh/Nm^3-H_2.
- When the RE cost in Brunei is US$0.05/kWh, the green hydrogen cost will be US$3.5–US$4.1/kg-H_2, and when the RE cost is US$0.07/kWh, the green hydrogen cost will be US$4.6–US$5.2/ kg-H_2, respectively.

Chapter 4
Potential Hydrogen Demand in Brunei Darussalam

This chapter provides a discussion on the potential hydrogen demand in Brunei in three sectors, i.e., power generation, road transport, and industrial sectors during the 2020–2050 period.
The discussion is based on other studies that ERIA has conducted:

- Kimura and Han (2021): an ERIA energy outlook for the East Asian Summit countries covering the 2020–2050 period that includes Brunei;
- Kimura et al. (2021): an ERIA study on Brunei focusing on the development of Temburong District as an ecotown; and
- Purwanto et al. (2023, forthcoming): a deep analysis of hydrogen demand in the ASEAN Member States' industry sectors and the possible future situations based on four climate ambition-related scenarios.

In each of the sectors, not only the hydrogen demand potential of Brunei is presented but also the total hydrogen demand potential of all ASEAN Member States (AMS).
Closing the chapter, a discussion on the aggregated total hydrogen demand potential in Brunei and the total of all AMS will be provided.

1. Potential Demand in Power Generation

In its Business-as-Usual (BAU) scenario, Kimura and Han (2021) estimate that power generation in Brunei will increase from around 2.54 terawatt-hours (TWh) in 2020 to around 4.90 TWh in 2050. In another scenario, i.e., the Alternative Policy Scenario (APS), the power generation in Brunei will reach around 4.70 TWh in 2050.

In Kimura and Han (2021), the BAU was developed for each East Asia Summit (EAS) country, including Brunei, outlining future sector and economy-wide energy consumption, assuming no significant changes to government policies. The APS, on the other hand, was set to examine the potential impacts if additional energy-efficiency goals, action plans, or policies being considered or likely to be considered were developed. The difference between the BAU and APS in final and primary energy supply represents potential energy saving, whilst the difference in the two scenarios' CO_2 emissions represents the potential to reduce them.

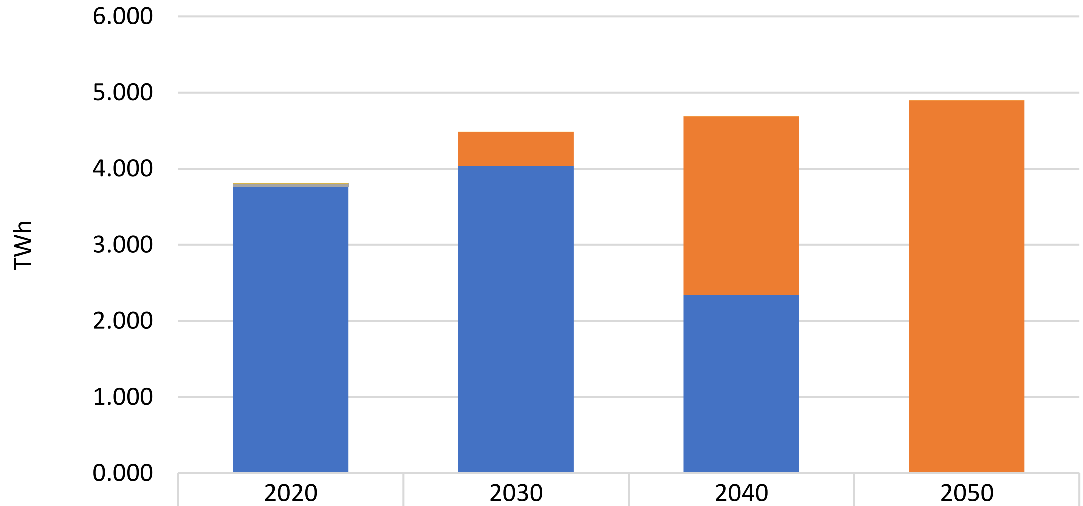
By 2020, electricity in Brunei Darussalam was 99% generated by natural gas-fired plants, with the remaining 1% by diesel-fired power plants. In the rest of the period of the BAU Scenario, i.e., 2030–2050, power in the country is entirely generated by natural gas-fired plants. In the APS, the share of natural gas during the same period is around 94% by 2030 and around 91% by 2040 and 2050, giving room for power generation by renewable energy resources, mainly solar PV.

To estimate the potential of hydrogen demand in the power sector, it is assumed that cofiring of natural gas and hydrogen will take place following an increasing share of hydrogen in natural gas-fired power plants, i.e., 0% by 2020, 10% by 2030, 50% by 2040, and 100% by 2050.

With this assumption, as shown consecutively in Figure 4.1 and Figure 4.2, by 2050, hydrogen needs in cofiring power plants in Brunei would reach around 4.9 TWh in the BAU Scenario and 4.6 TWh in the APS.

In terms of volume, if hydrogen cofiring at the gas-fired power plants has 60% efficiency, then Brunei will need around 20 kilotonnes per annum (ktpa) by 2030 in both scenarios. By 2050, the needed hydrogen will be around 230 ktpa in the BAU Scenario and around 200 ktpa per year in the APS.

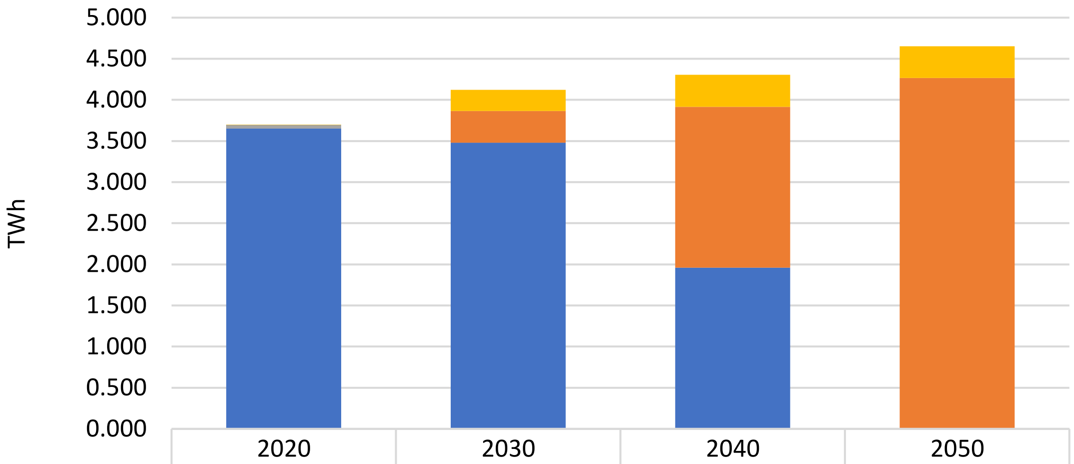
Figure 4.1. Brunei Darussalam's Estimated Power Generation Output with Hydrogen Cofiring – BAU Scenario



	2020	2030	2040	2050
Others	0.002	0.002	0.002	0.002
Oil	0.042	0.000	0.000	0.000
Hydrogen	0.000	0.448	2.344	4.897
Natural gas	3.763	4.035	2.344	0.000

BAU = Business-as-Usual Scenario of Kimura and Han (2021).
Note: Cofiring assumption of hydrogen in natural gas-fired power plants: 10% (2030), 50% (2040), and 100% (2050).
Source: Authors.

Figure 4.2. Brunei Darussalam's Estimated Power Generation Output with Hydrogen Cofiring – APS



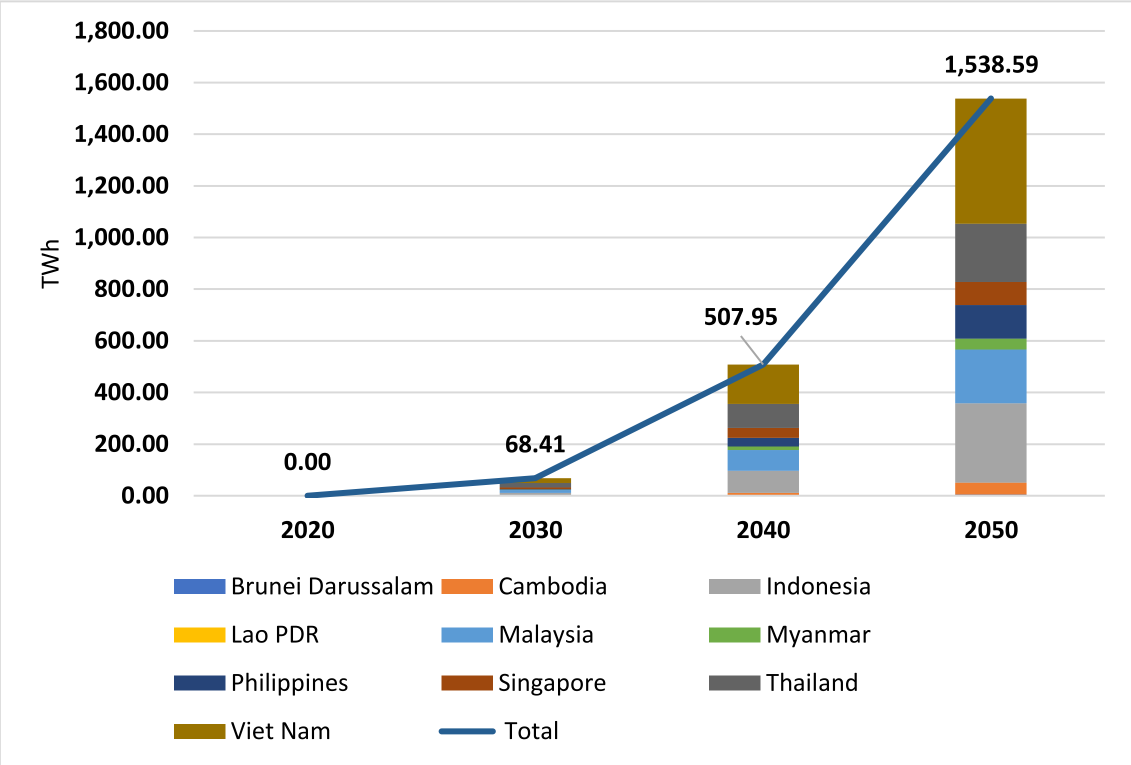
	2020	2030	2040	2050
Others	0.006	0.258	0.387	0.387
Oil	0.041	0.000	0.000	0.000
Hydrogen	0.000	0.386	1.958	4.265
Natural gas	3.652	3.478	1.958	0.000

APS = Alternative Policy Scenario of Kimura and Han (2021).
Note: Cofiring assumption of hydrogen in natural gas-fired power plants: 10% (2030), 50% (2040), and 100% (2050).
Source: Authors.

At the ASEAN level, Kimura and Han (2021) estimate that the total electricity of the 10 AMS generated in natural gas-fired power plants will grow from around 425 TWh in 2020 to 1,540 TWh in 2050 in the BAU Scenario and from around 400 TWh in 2020 to 1,270 TWh in 2050 in the APS.

Assuming also increasing rates of hydrogen cofiring in those gas-fired power plants in all AMS of 10% in 2030, 50% in 2040, and 100% in 2050, and an efficiency rate of 60% in hydrogen burning, the total power generation by cofiring at the ASEAN level in the BAU Scenario will grow from around 68 TWh in 2030 to around 1,540 TWh in 2050 (Figure 4.3) and in the APS from around 62 TWh in 2030 to around 1,272 TWh in 2050 (Figure 4.4).

Figure 4.3. ASEAN's Estimated Power Generation Output with Hydrogen Cofiring – BAU Scenario

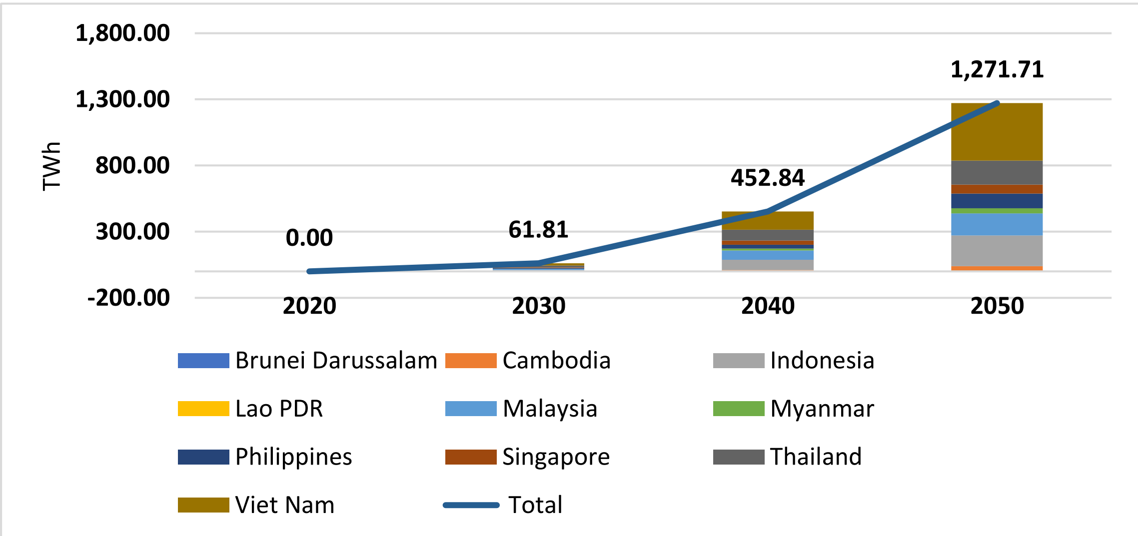


BAU = Business-as-Usual Scenario of Kimura and Han (2021).

Note: Cofiring assumption of hydrogen in natural gas-fired power plants: 10% (2030), 50% (2040), and 100% (2050).

Source: Authors.

Figure 4.4. ASEAN's Estimated Power Generation Output with Hydrogen Cofiring – APS Scenario



APS = Alternative Policy Scenario of Kimura and Han (2021).

Note: Cofiring assumption of hydrogen in natural gas-fired power plants: 10% (2030), 50% (2040), and 100% (2050).

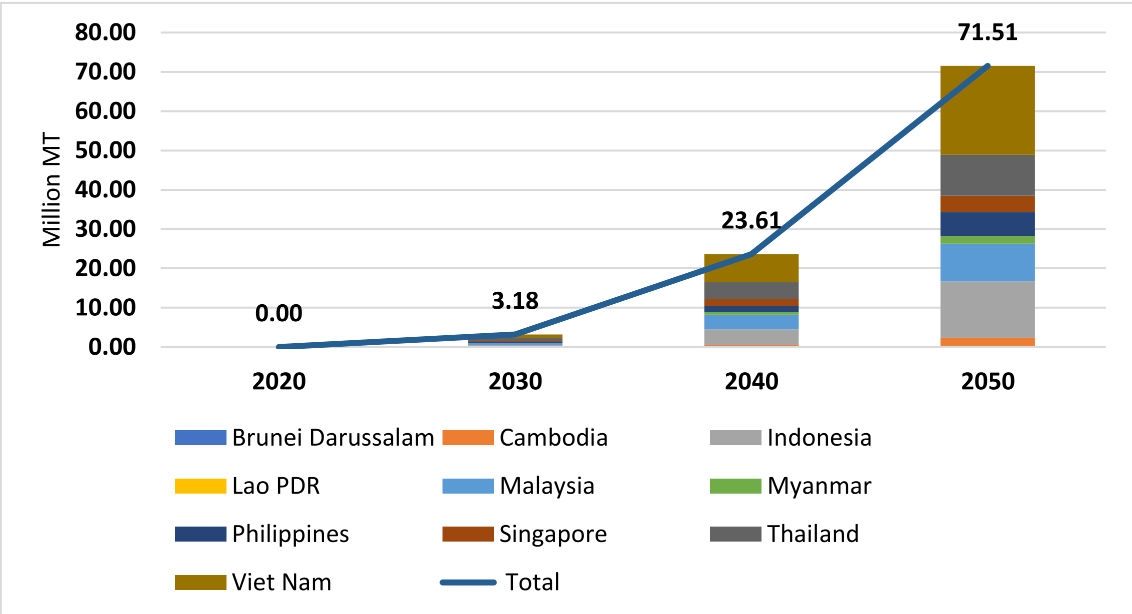
Source: Authors.

In terms of volume, the demand for hydrogen in the AMS in the BAU Scenario will grow from 3.2 million tonnes per annum (mtpa) in 2030 to 71.5 mtpa in 2050 (Figure 4.5), whilst in the APS Scenario it will grow from 2.8 mtpa in 2030 to 59 mtpa in 2050 (Figure 4.6).

Brunei Darussalam's share of total potential hydrogen demand in ASEAN is very small. In the BAU Scenario, it decreases from around 0.7% in 2030 to only around 0.3% in 2050, whilst in the APS, it drops from 0.6% in 2030 to 0.3% in 2050.

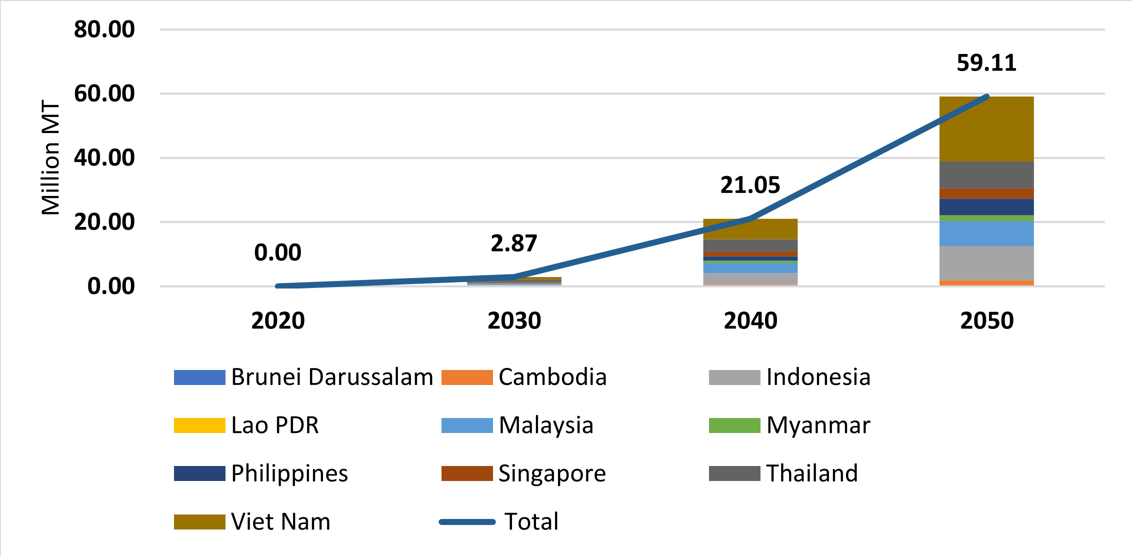
This decrease is not surprising, as Kimura and Han (2021) estimate that Brunei's generated electricity by gas-fired power plants will only grow with a compound average growth rate of slightly less than 0.5% during the 2030–2050 period, whilst that of ASEAN will be around 4% in the BAU Scenario and around 3.7% in the APS.

Figure 4.5. ASEAN's Estimated Hydrogen Demand for Cofiring in Power Generation – BAU Scenario



BAU = Business-as-Usual Scenario of Kimura and Han (2021).
Note: Cofiring assumption of hydrogen in natural gas-fired power plants: 10% (2030), 50% (2040), and 100% (2050).
Source: Authors.

Figure 4.6. ASEAN's Estimated Hydrogen Demand for Cofiring in Power Generation – APS Scenario



APS = Alternative Policy Scenario of Kimura and Han (2021).
Note: Cofiring assumption of hydrogen in natural gas-fired power plants: 10% (2030), 50% (2040), and 100% (2050).
Source: Authors.

2. Potential Demand in Road Transport

Kimura et al. (2020) study the impacts of hydrogen-powered fuel cell (FC) electric vehicles on Brunei's national energy systems and carbon dioxide emissions. For that purpose, they develop a BAU Scenario of road transport, i.e., the passenger car transport sector in Brunei to the 2050 horizon. This BAU Scenario is used as a benchmark scenario to assess the impacts of the penetration of new technologies in the passenger car fleet. In the scenario, the country's passenger car fleet develops to the horizon of 2050 without any penetration of battery electric or FC hydrogen cars. This scenario means that up to 2050, there will be only two kinds of passenger cars based on fuel type: gasoline-fuelled and diesel-fuelled passenger cars.

Three FC scenarios were elaborated to represent certain penetration levels of hydrogen-powered FC cars in the country's road passenger car fleet in 2017–2050. The level of penetration is represented by the exogenously defined percentages of shares of FCs in the total number of road passenger cars in Brunei in 2050. In all scenarios, we assumed that there is no FC in 2017, i.e., the base year.

The three main FC scenarios in Brunei are:

- FC10 – a scenario where FC hydrogen cars would comprise a 10% share of the total road passenger car fleet in 2050;
- FC20 – a scenario where FC hydrogen cars would comprise a 20% share of the total road passenger car fleet in 2050; and
- FC30 – a scenario where FC hydrogen cars would comprise a 30% share of the total road passenger car fleet in 2050.

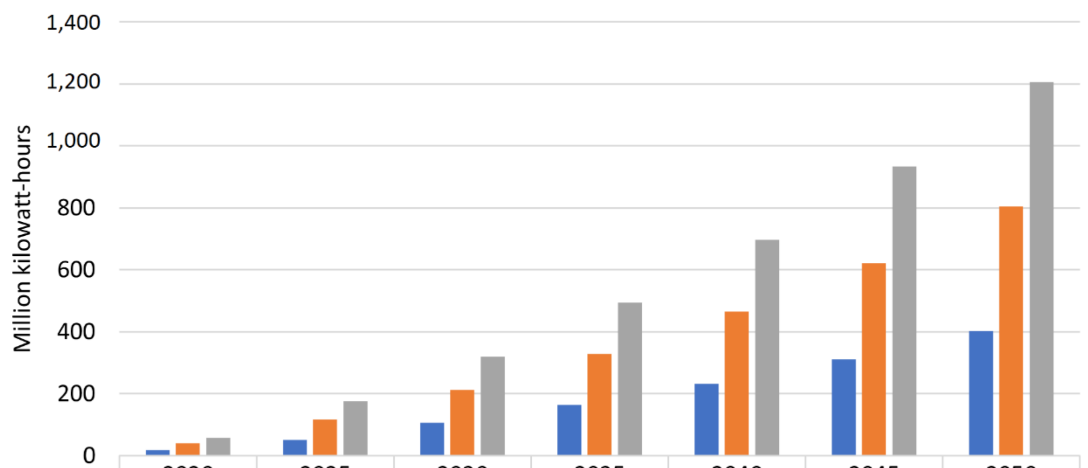
Based on historical data on passenger car ownership in Brunei Darussalam and the projected economic and socio-demographic conditions, Kimura et al. (2021) estimate the number of passenger cars in use in Brunei. The number of cars that are in use or active would grow from 270,000 units by 2017 to 370,000 by 2030, 455,000 by 2040, and 550,000 by 2050 with the ratio of gasoline-fuelled cars to diesel-fuelled cars being 70:30 during the whole period.

It is assumed that the FC efficiency of FCEVs is at 1.1 MJ/km or 3.27 km/kWh, i.e., in line with the specification of the compact hydrogen-powered fuel cell Toyota Mirai passenger car model FCA110 of the year 2015. The fuel economy of conventional passenger cars is assumed at 12.7 km/litre, whilst the average travel distance per passenger car is 24,000 km/year.

Using this assumption, in the BAU Scenario, between 2017 and 2050, energy demand from passenger car transport in Brunei would increase by around 12% per year from about 17 million gigajoules (GJ) in 2017 to approximately 36 million GJ in 2050, an increase of around 11% annually. The gasoline–diesel consumption ratio would be around 2:1, and full battery electric vehicles are assumed to enter the road passenger car fleet during the whole simulation period.

Figure 4.7 shows the hydrogen that needs to be produced in terms of energy in the country to meet the hydrogen demand in the FC scenarios. By 2050, the FC10 scenario would need about 400 GWh of hydrogen; FC20, about 800 GWh; and FC30, about 1,200 GWh of hydrogen.

Figure 4.7. Brunei Darussalam's Demand for Hydrogen in Terms of Energy in Three Hydrogen-powered Fuel Cell Vehicle Scenarios



	2020	2025	2030	2035	2040	2045	2050
FC10	19	50	106	164	232	311	402
FC20	39	117	213	329	465	622	804
FC30	58	176	320	493	697	934	1,206

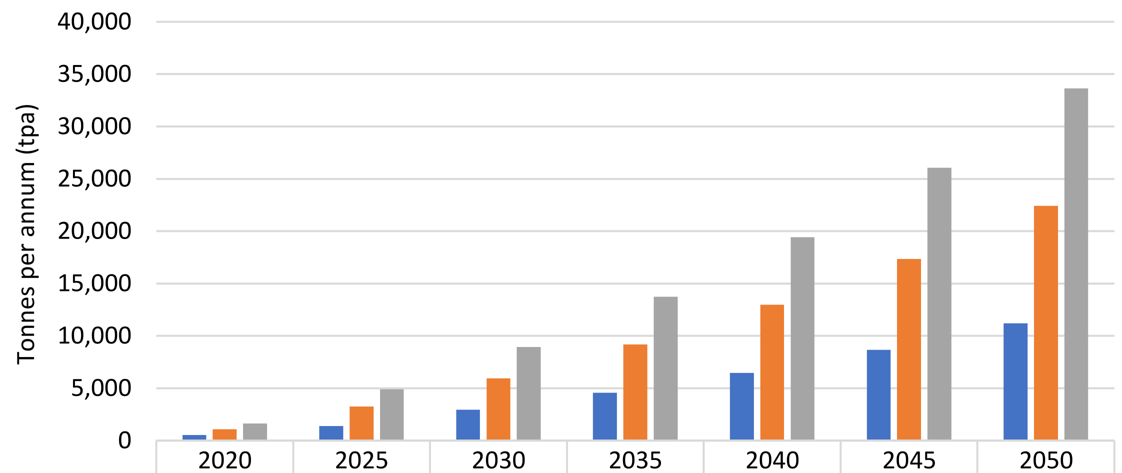
FC10 FC20 FC30

Note: FC10, FC20, and FC30 respectively represent scenarios of 10%, 20%, and 30% shares of fuel cell electric vehicles in the total road passenger car fleet by 2050, based on Kimura et al. (2021).
Source: Kimura et al. (2021).

The efficiencies of electrolysers to produce hydrogen are assumed at 67% between 2017 and 2020, and at 85% by 2030 and beyond, whilst between 2020 and 2030, the efficiency percentages are assumed to grow linearly from 67% to 85%.

In terms of volume, in the FC10 Scenario, Brunei's demand for hydrogen will grow from 530 tonnes per annum (tpa) in 2020 to 11,210 tpa in 2050. On the other hand, in the FC30 scenario, hydrogen demand will increase from 1,620 tpa in 2020 to 33,630 tpa in 2050. The FC20 scenario is between the other two scenarios, i.e., from 1,088 tpa in 2020 to 22,421 tpa in 2050.

Figure 4.8. Brunei Darussalam's Estimated Hydrogen Demand from the Road Transport Sector



	2020	2025	2030	2035	2040	2045	2050
FC10	530	1,394	2,956	4,573	6,470	8,673	11,210
FC20	1,088	3,263	5,940	9,175	12,967	17,345	22,421
FC30	1,617	4,908	8,924	13,748	19,437	26,046	33,631

Note: FC10, FC20, and FC30 respectively represent scenarios of 10%, 20%, and 30% shares of fuel cell electric vehicles in the total road passenger car fleet by 2050, based on Kimura et al. (2021).
Source: Kimura et al. (2021).

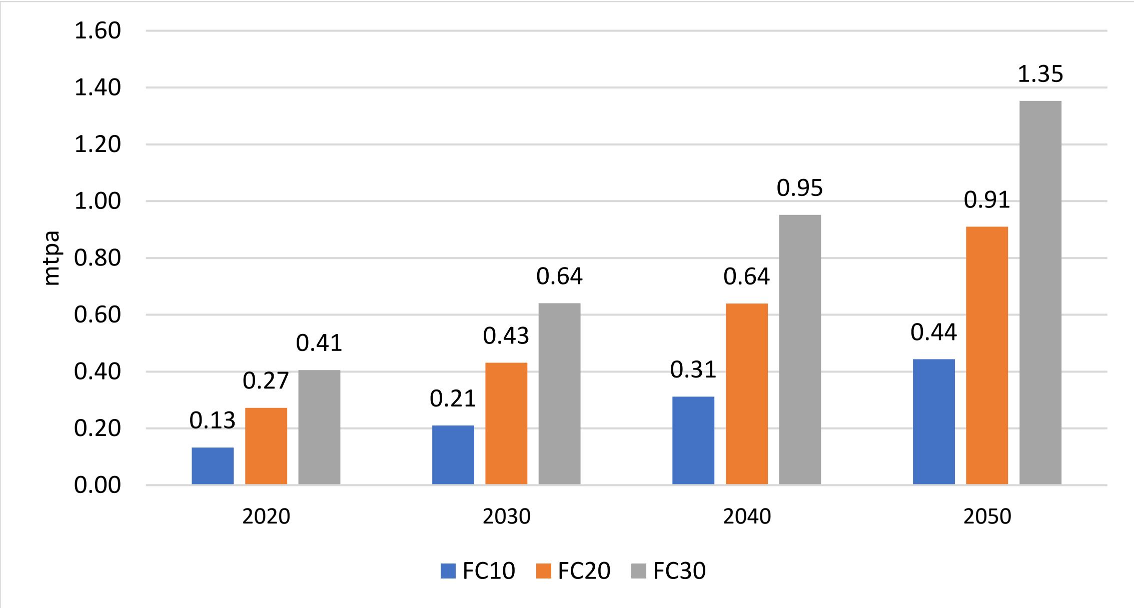
It is assumed that the effects of the F10, F20, and F30 scenarios on energy demand in the road transport sector in all ASEAN countries will be the same as in Brunei, i.e., the shares of energy in road transport that are shifted to hydrogen power FCEVs in the three scenarios in Brunei will be the same as in other ASEAN countries. Using this assumption, it is possible to estimate the needed hydrogen at the ASEAN level in each of the three hydrogen scenarios and in each of the Kimura and Han (2021) scenarios, namely the BAU and APS scenarios.

By 2030, hydrogen demand for road transport in ASEAN might reach 0.21 mtpa, 0.43 mtpa, and 0.64 mtpa in the BAU scenario in the FC10, FC20, and FC30 FCEV scenarios, respectively, and 0.18 mtpa, 0.37 mtpa, and 0.56 mtpa in the APS in the FC10, FC20, and F30 FCEV scenarios, respectively.

By 2050, hydrogen demand for road transport in ASEAN might reach 0.44 mtpa, 0.91 mtpa, and 1.35 mtpa in the BAU scenario in the FC10, FC20, and FC30 FCEV scenarios, respectively, and 0.34 mtpa, 0.70 mtpa, and 1.05 mtpa in the APS in the FC10, FC20, and F30 FCEV scenarios, respectively.

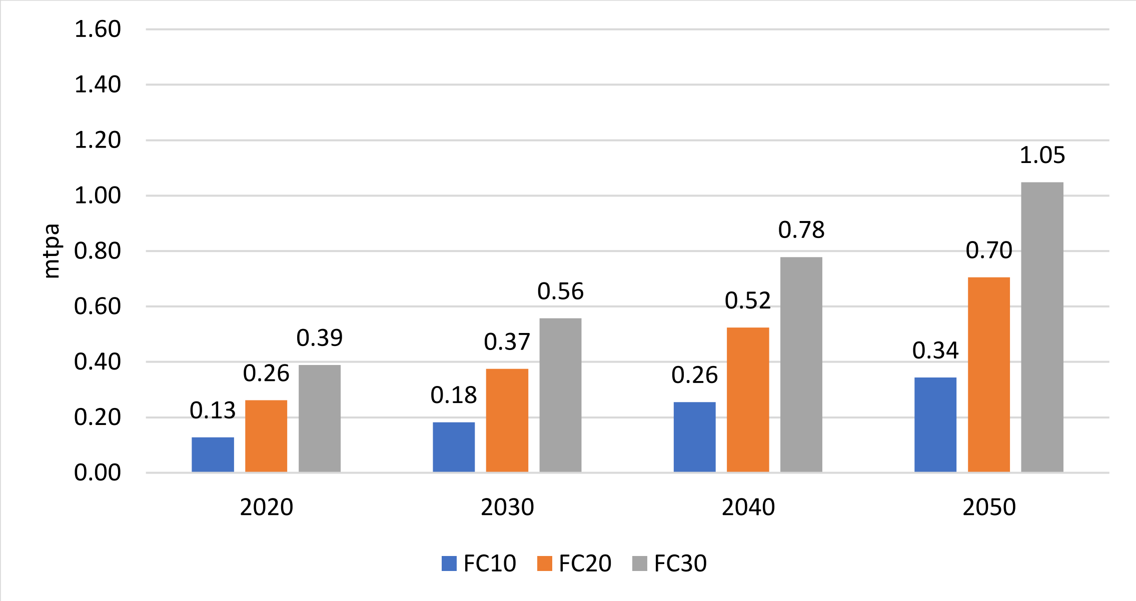
Figure 4.9 and Figure 4.10 show the estimated demand for hydrogen from road transport in both the BAU and APS scenarios differentiated by the FCEV penetration scenarios, i.e., FC10, FC20, and FC30.

Figure 4.9. ASEAN's Estimated Hydrogen Demand from the Road Transport Sector – BAU Scenario



Note: FC10, FC20, and FC30 respectively represent scenarios of 10%, 20%, and 30% shares of fuel cell electric vehicles in the total road passenger car fleet by 2050, based on Kimura et al. (2021).
Source: Kimura et al. (2021).

Figure 4.10. ASEAN's Estimated Hydrogen Demand from the Road Transport Sector – APS



Note: FC10, FC20, and FC30 respectively represent scenarios of 10%, 20%, and 30% shares of fuel cell electric vehicles in the total road passenger car fleet by 2050, based on Kimura et al. (2021).
Source: Kimura et al. (2021).

3. Potential Demand in the Industry Sector

Purwanto et al. (2023, forthcoming) aim to provide a set of policy recommendations for policymakers in AMS to accelerate the process of obtaining a hydrogen supply with lower carbon intensity in the industrial sector, as part of an optimal hydrogen market development strategy for the ASEAN region. The study departs from the fact that current hydrogen use in ASEAN countries is entirely absorbed in industry sectors, and that this hydrogen is almost entirely produced via conventional steam methane reforming with high carbon intensity.

According to Purwanto et al. (2023, forthcoming), hydrogen demand in Brunei's industry sector grew from around 39,150 tpa in 2015 to around 41,960 tpa in 2020, with slightly more than 92% of this demand coming from the oil refining sector and the rest coming from the chemical industry sector. In fact, this hydrogen use in oil refining and the chemical industry is practically the only current use of hydrogen in Brunei. In other words, apart from use in the industry sectors, hydrogen is not used elsewhere. This is not only the case in Brunei but also in other ASEAN countries and most countries in the world.

Still, according to the study, at the ASEAN level, the hydrogen demand of the region grew from around 3.270 mtpa in 2015 to around 3.680 mtpa in 2021. Hydrogen demand in Brunei's industry sector comprises only around 1% of the ASEAN total.

The study considers four future scenarios for the development of hydrogen demand and supply in the industry sectors.

- The ERIA-Frozen scenario relates to a future situation where the trend as shown in the demand and supply of hydrogen in the 2015–2021 period continues as it is. It assumes that

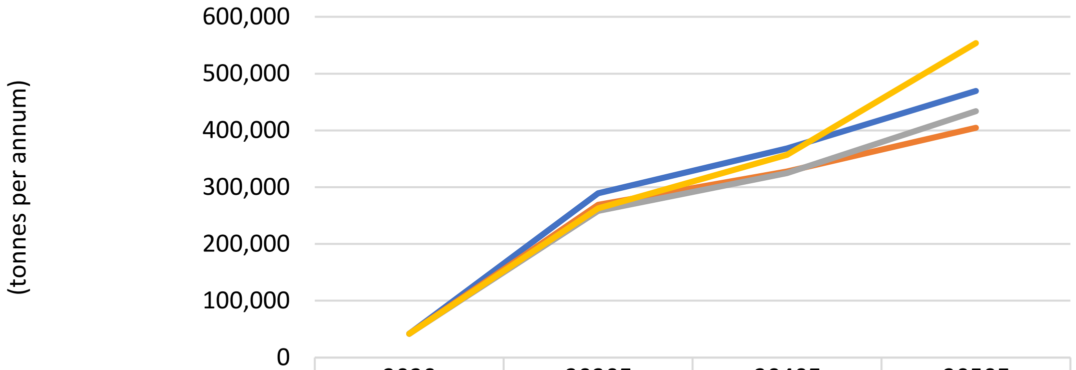
ASEAN countries only maintain a business-as-usual approach without any national CO_2 or renewable energy or energy efficiency (RE/EE) targets to meet. Here, hydrogen demand and supply in the future grow at the same average rate as during the 2015–2020 period, and supply, including announced capacity expansion, will be able to meet demand using the same supply structure as during the 2015–2020 period.

- The ERIA-STEPS scenario is inspired by the Stated Policies Scenario (STEPS) described by the International Energy Agency (IEA) (2022a; 2022b). Basically, it retains the current and the latest AMS policies, including those related to the intended nationally determined contribution (INDC). The scenario has no particular outcome to achieve, meaning that there is no additional policy implementation apart from the implementation based on the INDC, e.g. shifting to a certain percentage of renewable use in power generation at a certain point in time, or increasing energy efficiency in several final sectors, etc. The scenario explores where the energy system might go without additional policy implementation and takes a granular, sector-by-sector look at existing policies and measures and those under development without any guarantee that the intended CO_2 emissions reduction will be achieved.
- The ERIA-APS scenario is based on the Announced Pledges Scenario of the IEA (2022b) that assumes that all aspirational targets announced by governments are met on time and in full, including their long-term net zero and energy access goals. Government targets in the scenario are assumed to be achieved on time and in full. The scenario includes all the climate commitments made by governments around the world, including INDCs and longer-term NDC targets, and assumes that they will be met in full and on time to fill the 'implementation gap' that needs to be closed by countries in the STEPS scenario to achieve their announced decarbonisation targets. The scenario includes net zero pledges as announced by countries, in this case, ASEAN countries' pledges.
- The ERIA-Likely Scenario represents the most likely future situation in the supply and demand of hydrogen in the four industrial sectors in ASEAN from the present time to the 2050 horizon. It is inspired by the forecast of hydrogen demand by DNV (2022). In this scenario, hydrogen produced globally to be used as feedstock would grow from around 90 mtpa in 2020 to reach 195 mtpa in 2050, whilst demand for hydrogen and its derivatives in Southeast Asia would reach 4.1% of the global total by 2050.

An ammonia plant, Brunei Fertilizer Industries (BFI, 2022), entered production in 2022 with installed maximum capacity of 3,900 tonnes per day (tpd) of ammonia and, for all cases, this fact is considered in the calculation of the future supply and demand of hydrogen of Brunei's industry sectors.

Following the four scenarios in Purwanto et al. (2023), Brunei's hydrogen industry demand by 2050 might reach from around 404,550 tpa as in the ERIA-STEPS Scenario to as high as 553,650 tpa as in the ERIA-APS Scenario (Figure 4.11).

Figure 4.11. Brunei Darussalam's Estimated Hydrogen Demand from the Industry Sectors – Four Scenarios



	2020	2030E	2040E	2050E
ERIA-Frozen Scenario	41,957	289,337	368,377	469,431
ERIA-STEPS Scenario	41,957	268,779	327,380	404,545
ERIA-Likely Scenario	41,957	258,104	324,740	433,837
ERIA - APS Scenario	41,957	262,842	356,793	553,653

Source: Purwanto et al. (2023, forthcoming).

The demand growth for hydrogen in the industry sectors in Brunei is shown in detail in Figure 4.11.

In the ERIA-Frozen Scenario, demand for hydrogen is driven by the increasing demand in oil refining due mainly to the increasing use of transport fuels, i.e. gasoline and diesel demand from cars that are assumed not to be electrified.

In the ERIA-STEPS scenario, the electrification of mobility, marked by the increasing penetration of EVs, reduces hydrogen demand in the oil refining sector, and therefore the total hydrogen demand in this scenario is lower by 2050 compared to the ERIA-Frozen Scenario.

In the ERIA-Likely scenario, EV penetration is stronger than in the ERIA-STEPS scenario, and the demand for hydrogen in oil refining in this scenario is lower than in the ERIA-STEPS scenario. On the other hand, demand for ammonia fuels used, for example, in short sea shipping or ammonia as a carrier would start to kick in in this scenario so that hydrogen needed in the ammonia industry in this scenario is higher compared to the ERIA-Frozen and ERIA-STEPS Scenarios.

Finally, the ERIA-APS Scenario sees the strongest mobility electrification and the strongest demand growth in ammonia fuels. The growth of hydrogen demand in the ammonia industry offsets the decrease in hydrogen demand in oil refining, and this scenario has the highest hydrogen demand in 2050 compared to the other three scenarios.

It is important to note that it is not only the quantity of hydrogen that changes between the scenarios but also the intensity of carbon in the production of hydrogen itself. The hydrogen used in the industry sectors reaches the lowest carbon intensity in the ERIA-APS Scenario and the highest in the ERIA-Frozen Scenario.

Finally, by 2050, Brunei's part in the total hydrogen demand in the industry sectors in ASEAN reaches 5.7% in the ERIA-Frozen Scenario, 5.5% in the ERIA-STEPS Scenario, 5.4% in the ERIA-Likely Scenario, and 4.7% in the ERIA-APS Scenario. This decreasing percentage share with the decreasing carbon intensity of hydrogen reflects the importance of demand coming from the oil refining industry in the country, which decreases proportionally with the increasing electrification of road mode transport.

Table 4.1. Brunei Darussalam's Estimated Hydrogen Demand by Industry Sector – Four Scenarios

	2020	2030E	2040E	2050E
ERIA-Frozen Scenario				
Ammonia	0	154,243	200,939	261,772
Refinery	38,748	126,065	155,186	191,034
Methanol	0	0	0	0
Iron and steel	0	0	0	0
Chemical and others	3,209	9,028	12,252	16,626
Total	41,957	289,337	368,377	469,431
ERIA-STEPS Scenario				
Ammonia	0	133,685	181,292	245,832
Refinery	38,748	126,065	133,837	142,087
Methanol	0	0	0	0
Iron and steel	0	0	0	0
Chemical and others	3,209	9,028	12,252	16,626
Total	41,957	268,779	327,380	404,545
ERIA-Likely Scenario				
Ammonia	0	132,413	205,530	318,981
Refinery	38,748	115,803	105,793	96,648
Methanol	0	0	0	0
Iron and steel	0	0	0	0
Chemical and others	3,209	9,887	13,417	18,207
Total	41,957	258,104	324,740	433,837
ERIA-APS Scenario				
Ammonia	0	132,682	246,347	457,305
Refinery	38,748	120,720	97,635	78,965
Methanol	0	0	0	0
Iron & steel	0	0	0	0
Chemical & others	3,209	9,440	12,810	17,384
Total	41,957	262,842	356,793	553,653

Source: Purwanto et al. (2023, forthcoming).

4. Total Potential Demand

By 2050, total hydrogen demand in Brunei Darussalam could be as low as 0.68 mtpa to as high as 0.81 mtpa, whilst in the same year, in ASEAN, it could be from 67.7 mtpa to 84.5 mtpa. By 2050, Brunei's total share of hydrogen demand in ASEAN will be around 0.9%–1.2%.

The structure of the demand will change differently in Brunei compared to ASEAN. Currently, 100% of hydrogen is consumed in the industry sectors in all ASEAN countries. By 2050, in Brunei, hydrogen demand from the industry sectors will range from 60% to 72% of the total hydrogen demand of the country. Nevertheless, at the ASEAN level, by the same year, the share of the industry sectors in total hydrogen demand will be only around 9%–16%.

The use of hydrogen in power generation, i.e. in cofiring with natural gas, plays an important role in this different pathway. In Brunei, power demand growth between 2020 and 2050 will be around 0.4%–0.5% per year, whilst the average growth in ASEAN during the same period will be around 3.7%–4.2% per year.

With the development of the ammonia industry in Brunei Darussalam, the country will have the chance to participate in the development of ammonia fuels or ammonia as a carrier. If the carbon intensity of hydrogen production can be reduced significantly, then low-carbon ammonia can be a commodity that Brunei can put forward to participate in the energy transition in ASEAN, and this has been shown by the increasing demand for the ammonia industry in the ERIA-APS Scenario.

Chapter 5
Economic Impact of Green Hydrogen Production

1. Historical Trend of Oil and Gas Production

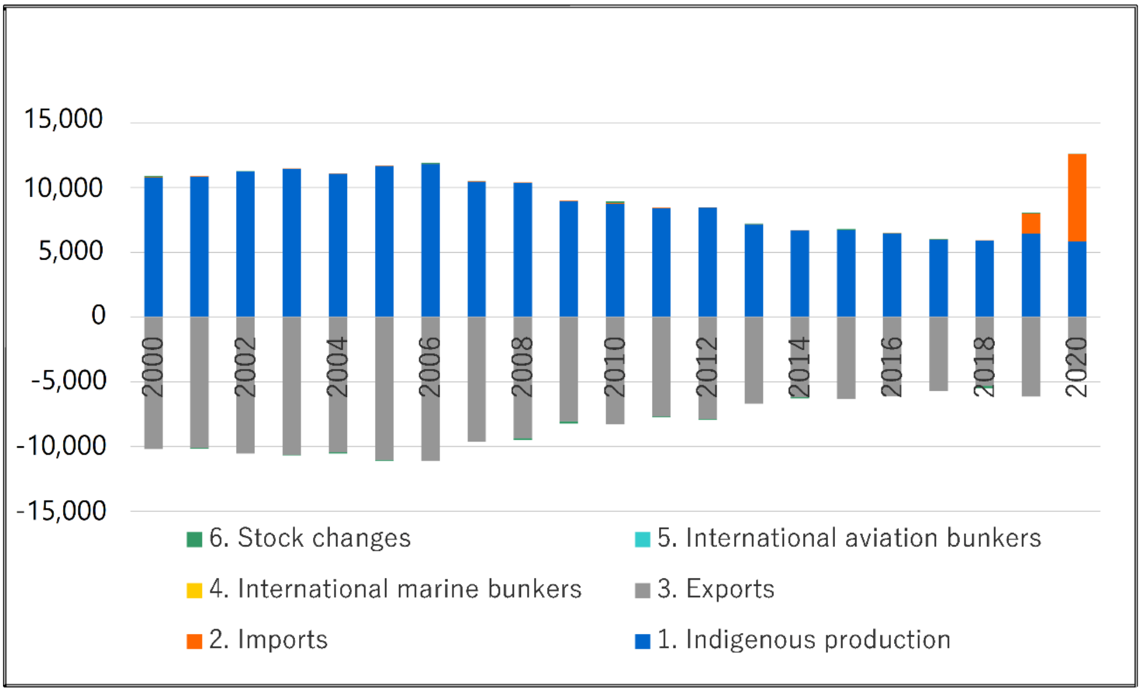
Brunei Darussalam is a famous country in terms of oil and natural gas production, and exports of oil and gas are important for the country's national income. Thus, this section reviews the historical production of crude oil, petroleum products, and natural gas.

1.1. Crude Oil Production

Brunei kept its crude oil production at more than 10,000 kilotonnes of oil equivalent (ktoe) (approximately 10 petalitres) until 2006, but after that, its production declined until 2018 and was just above 5,000 ktoe in 2020. In this regard, crude oil exports have been also decreasing. However, since 2019, Brunei started to import crude oil for refinery process use, and its import amount was larger than its crude oil production in 2020 (Figure 5.1).

Figure 5.1. Supply and Demand of Crude Oil in Brunei Darussalam

(ktoe)



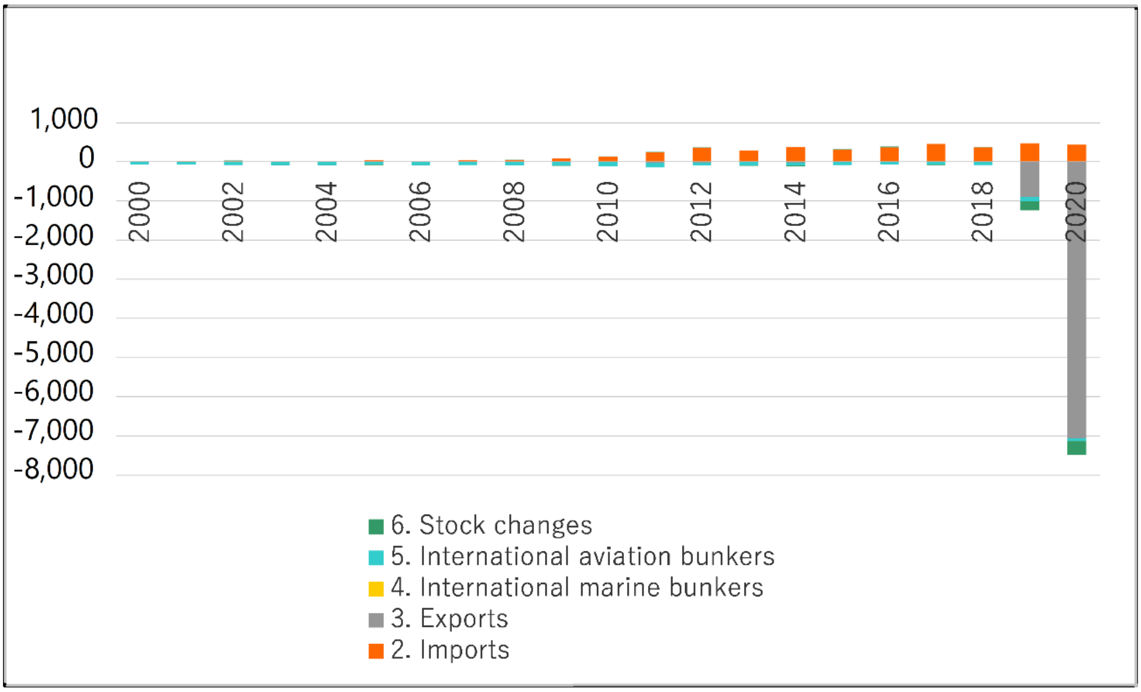
Source: APEC Energy Database operated by the Asia Pacific Energy Research Centre.

1.2. Petroleum Product Production

Brunei's petroleum production had been limited due to its small refinery capacity. Consequently, it imported petroleum products mainly from Singapore in response to increasing petroleum demand from 2009. However, it started its refinery operations in 2019, and thus also started to export petroleum products to neighbouring countries and other countries (see Figure 5.2).

Figure 5.2. Supply and Demand of Petroleum Products in Brunei Darussalam

(ktoe)



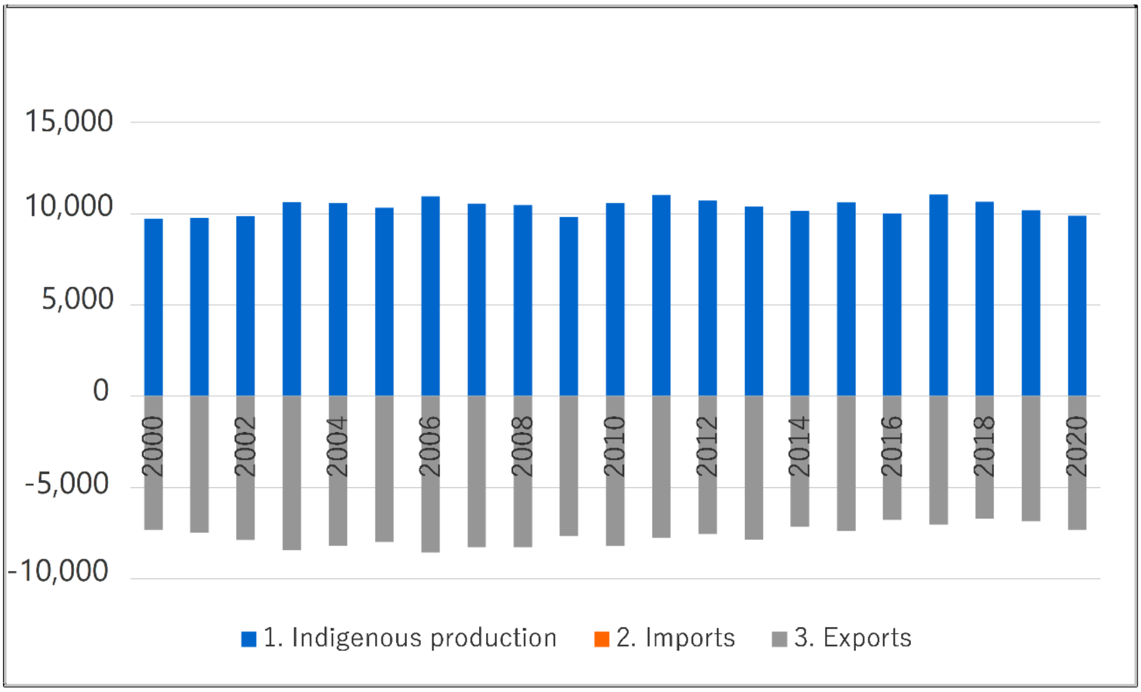
Source: APEC Energy Database operated by the Asia Pacific Energy Research Centre.

1.3. Natural Gas

Brunei has produced natural gas constantly at around 10,000 ktoe per year over the past 20 years, and its exports have also been around 7,000–8,000 ktoe per year. Natural gas has been a key player in terms of maintaining national income, however its production shows a downward trend in the last years (see Figure 5.3).

Figure 5.3. Supply and Demand of Natural Gas in Brunei Darussalam

(ktoe)

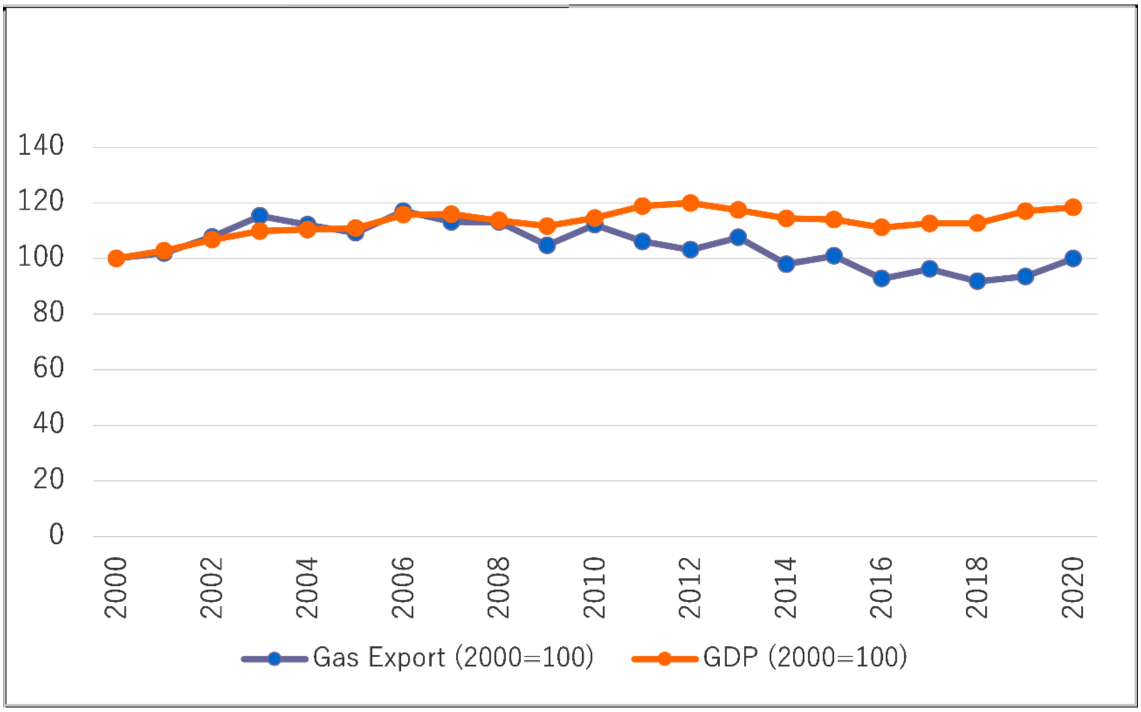


Source: APEC Energy Database operated by the Asia Pacific Energy Research Centre.

2. Relationship between Natural Gas Exports and Economic Growth

Figure 5.4 shows the relationship between natural gas exports (in ktoe) and gross domestic product (GDP) (in constant local currency units). Both natural gas exports and GDP increased from 2000, but natural gas exports showed a downward trend after 2010 and were lower than the 2000 level after 2015. On the other hand, GDP remained 20% higher than the 2000 level. One reason is that Brunei exports not only natural gas but also crude oil and methanol, and after 2019, Brunei started to export petroleum products. In addition, an increase in final demand, especially governmental expenditure and gross capital formation, such as investment in new refinery plants, also contributed to this gap (see Figure 5.4).

Figure 5.4. Relation between Natural Gas Exports and Economic Growth



Source: World Bank, World Development Indicators 2022; APEC Energy Database operated by the Asia Pacific Energy Research Centre.

3. Change in GDP Components

GDP consists of the following economic components:

Cp : Final private consumption (household expenditure)

Cg : Final governmental consumption (national administration expenditure)

I : Gross fixed capital formation (investment)

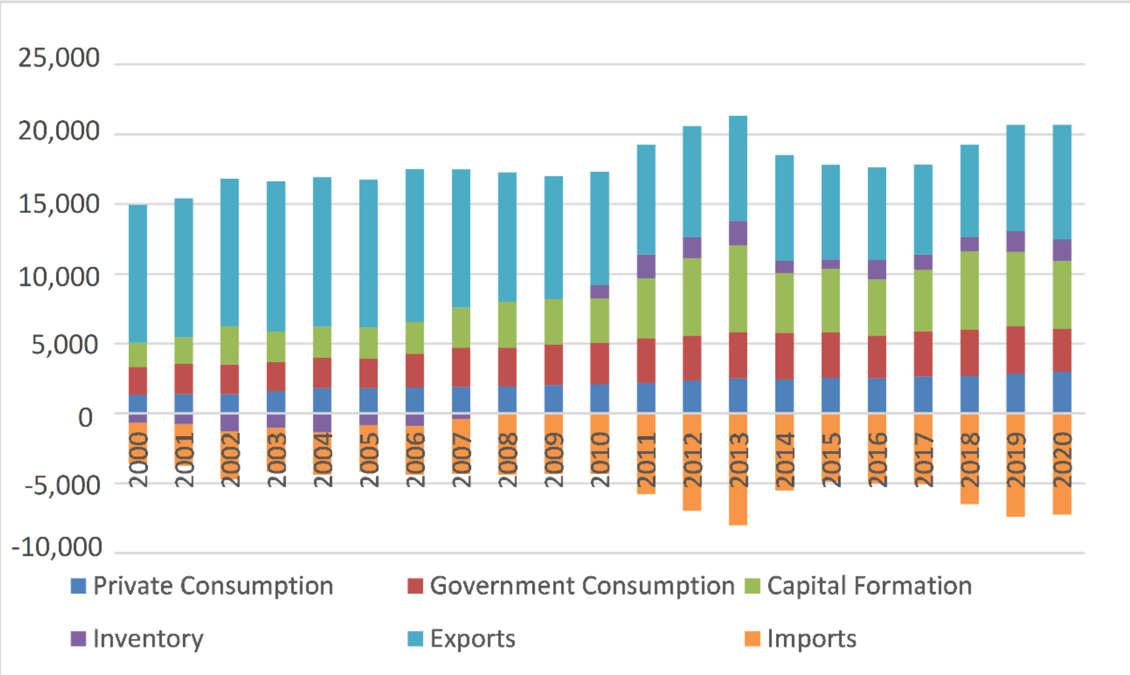
J : Inventory (stock change)

E : Exports (oil and gas mainly)

M : Imports (food, consumer, and capital goods)

GDP is defined as Cp + Cg + I + J + E – M. Looking at Figure 5.5, exports have been a dominant component for Brunei, and oil and gas exports surely contributed directly to the country's GDP growth. However, their share has decreased recently, whilst capital formation has been increasing due to the construction of a new refinery as well as a methanol plant and a hydrogen demonstration plant, etc. The share of final consumption, which consists of private and government consumption, has been not significant compared to exports, but its share has been increasing year by year. In 2012 and 2013, imports rose along with capital formation. One reason was that the construction of the new refinery used imported machines and equipment from China.

Figure 5.5. GDP Components of Brunei Darussalam

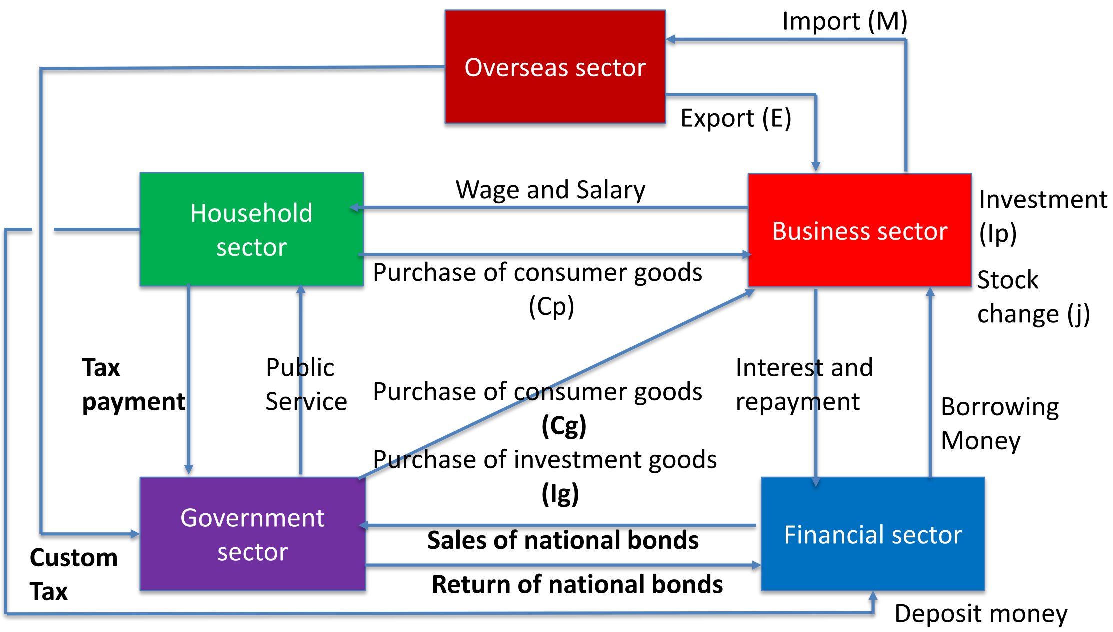


Source: World Bank, World Development Indicators 2022.

4. Economic Structure

This section provides details on the concept of the economic activities of a country. The business sector, in other words private companies, hires employees and constructs factories for producing consumer or capital goods. Meanwhile, the household sector purchases consumer goods from the domestic market using the wages and salary paid by the business sector, and this is called final private consumption. The business sector and household sector pay taxes to the government sector so that the government sector also purchases consumer goods from the domestic market. This is final government consumption. The business sector sells consumer goods to foreign countries, which are called exports. If the business sector imports consumer goods from foreign countries, these are called imports, and it sells the imported goods to the domestic market. Capital goods are treated the same as consumer goods. When the business sector purchases equipment and machinery, this is called private fixed capital formation or investment. If the household sector purchases standalone houses or condominiums, these are also classified as private fixed capital formation investment. When the government sector constructs office buildings and purchases equipment, this is called government capital formation or investment. Private + government investment is called gross fixed capital formation or investment. Inventory or stock changes mean that the business sector produces consumer goods, but if they are not sold in a period, they should be accounted for as stock change. The financial sector is a key player in supporting economic activities by the business, household, and government sectors that are not reflected directly in GDP. The financial sector engages stable money flows amongst the business, household, and government sectors (see Figure 5.6).

Figure 5.6. Simplified Economic Structure of a Country



Source: Authors.

5. Economic Contribution of Green Hydrogen Production

If Brunei will produce green hydrogen using renewable electricity, the following facilities are needed:

a. A solar PV system, especially the floating type
b. Water electrolysis

This section analyses the economic impacts of the installation of these two facilities.

5.1. Solar PV Systems

The estimated capacity of an installed solar PV system is 2,154 MW (see Chapter 2). If we assume the cost of a solar PV system cost is US$800/kW, the estimated investment cost of a solar PV system is US$1,723.2 million:

2,154 (MW) x 800 (US$/kW) = US$ 1,723.21, million

The gross fixed capital formation of Brunei in 2019 was B$7 billion, so converting to US dollars:

7,000 (B$ million) / 1.36 (B$/US$) = 5,147 (US$ million)

Solar PV system investment accounted for 33% of gross fixed capital formation in 2019 and was significant. But if Brunei will import all solar PV equipment from foreign countries, an economic repercussion effect cannot be expected.

In addition to an investment effect, the following economic benefits are expected:

a. Some of the investment (such as 10% of US$1,723.2, million) will go to local civil engineering companies.

b. Some labour is expected to be hired at the operation stage of the solar PV system.

Based on the capital cost of the solar PV system, if we assume 20 years as its service life and 8% of capital costs as its operation cost, its generation cost is estimated using 17% of the capacity factor as follows:

(1,723.2, / 20 + 1,723.2*0.08) / (2,154*24*365*0.19) = US$0.0624/ kWh

5.2. Electrolysers

Usually, the unit capital cost of an electrolyser facility is defined as US$/kWe, and it is estimated at US$1,100–US$1,800 per kWe in the case of a Polymer Electrolyte Membrane (PEM) electrolyser according to open sources. However, this time, if we assume a cost of US$1,050, expecting innovative technology development in the future, the capital cost of the electrolyser facility is estimated as follows:

Electricity coming from the solar PV system: 2,154 (MW) x 19% (capacity factor) = 409.26
Capital cost of the electrolyser: 409.26 (MW) x 1,050 (US$/kWe) = US$429.7 million

Then, the hydrogen production cost is estimated as follows:

Depreciation: (1,723.2 + 429.7) / 20 =107.64 (US$ million)
Operation cost: (1723.2 + 429.7) x 8% = 172.2 (US$ mill
Hydrogen production cost: (107.6 + 172.2) / 65.7 (kilotonnes) = US$4.2584 per kg-$H_2$

The capital cost of the electrolyser is estimated at US$429.7million, and it is just 25% of the solar PV system. But it is still significant in Brunei's annual gross fixed capital formation and should provide an effective economic repercussion effect for Brunei if the country produces the electrolyser equipment by itself. In addition, as for the solar PV system, Brunei expects profits for local civil engineering companies and an increase in employees to work at the electrolyser plant.

6. Possibility of Energy Exports

Brunei is famous for oil and gas production and exports, but will it export oil and gas continuously? In the energy transition period, from now to 2030–2035, the world will shift from coal power plants to gas power plants and use both internal combustion engine vehicles and EVs, and Brunei will be able to export oil and gas continuously. After 2040, the world will become carbon neutral by 2050 or 2060, so Brunei will not be able to export oil and gas due to a lack of demand. But Brunei will be a potential country for exporting clean energy in the form of green or blue hydrogen or ammonia. Green hydrogen will be produced by electricity from solar PV systems, and blue hydrogen will be produced from natural gas and oil with carbon capture and storage (CCS). Then, clean ammonia will be produced from green and blue hydrogen. This point is very important if Brunei will be an energy exporting country continuously until 2050 or 2060.

7. Competitiveness of Green Hydrogen Production

Not only Brunei but also other countries and regions will produce and export hydrogen to the world. Brunei's competitors are Sarawak province (Malaysia), Indonesia, Australia, India, and Middle Eastern countries. A simple comparison of the hydrogen production costs between Brunei and Middle Eastern countries is shown below:

a. Brunei's hydrogen production cost using a solar PV system:

- Capital cost of solar PV (10 MW): 800 (US$/KW) x 10 x 1000 (KW) = US$8 million
- Depreciation period: 20 years
- Capacity factor: if 19%, 16,644 MWh
- Generation cost: US$0.02403/kWh

b. Middle Eastern countries:

- Capital cost of solar PV (10 MW): 800 (US$/KW) x 10 x 1000 (KW) = US$8 million
- Depreciation period: 20 years
- Capacity factor: if 25%, 21,900 MWh
- Generation cost: US$0.01826/kWh; 24% lower than Brunei

The difference between Brunei and Middle Eastern countries is just the capacity factors, which are 19% in Brunei and 25% in the Middle East, due to different climate conditions. But in the case of the Middle East, countries need to transport hydrogen to the ASEAN region as for oil and gas. Thus, Brunei could have an advantage over green hydrogen produced in the Middle East if the hydrogen transport cost from the Middle East to Asia is expensive.

If the cost of green hydrogen produced in Brunei Darussalam is higher than in other countries, such as Middle Eastern countries and Australia, Brunei's green hydrogen will not be accepted due to economic reasons. Thus, blue hydrogen is still an option for Brunei.

8. Business Investment for the Clean Hydrogen Industry

As a result, Brunei will continue to produce clean energy in the form of blue and green hydrogen and export it to foreign countries, like oil and gas. Brunei will need to invest in blue and green hydrogen production facilities to replace oil and liquefied natural gas production facilities. Thus, Brunei will not change its business model because it will just change the type of energy from fossil fuels to clean hydrogen. In the case of blue hydrogen, CO_2 emitted from the process of producing hydrogen from natural gas should be treated by applying CCS technology because Brunei has a large potential capacity for CO_2 storage or carbon recycling (CR) technology, which produces synthetics fuels (known as e-fuel) based on the captured CO_2 and produced clean hydrogen. Brunei can consume synthetic fuels like gasoline and diesel oil internally or export them to foreign countries. Consequently, Brunei will need to invite international enterprises to start clean energy business in the country. Brunei already has experience and expertise in inviting international companies, such as Shell and Mitsubishi Corporation, so the government is focusing on setting up environmental and safety regulations for hydrogen and CCS/CR referring to the existing oil and gas regulations. In addition, the government is taking leadership in initiating the standardisation of hydrogen and CO_2 trade in the Asia-Pacific and ASEAN regions.

Chapter 6
Conclusions and Recommendations

Becoming carbon neutral towards 2050 or 2060 is a crucial target for the world, including the ASEAN region, and, consequently, hydrogen is highlighted because it can be combusted the same as fossil fuels but does not emit CO_2. There are two types of hydrogen: green hydrogen and blue hydrogen. Green hydrogen is produced by electrolyser technology using clean electricity generated by renewable energy. Blue hydrogen is produced from fossil fuels by applying reforming and gasification technology with CCS. Brunei is a rich blue hydrogen country due to its large oil and gas reserves. On the other hand, Brunei is poor in renewable energy and only solar PV systems are available in limited amounts due to the small land area. Thus, floating solar PV systems are an option for Brunei for applying to reservoirs, rivers, wetlands, and Brunei Bay. This study firstly estimated the potential capacity of solar PV systems, mainly the floating type, in Brunei (2,387 MW) and after that, based on the solar PV power generation, potential hydrogen production was forecasted (73.4 kilotonnes/year). Next, the study forecasted the future hydrogen demand in the ASEAN region, including Brunei (70 million tonnes/year in 2040). Thus, in addition to green hydrogen, Brunei has to produce blue hydrogen to meet its future hydrogen demand and that of other neighbouring countries. Investment in floating solar PV systems and electrolyser facilities will be huge for Brunei (US$2,300 million), comprising around 40% of the country's gross capital formation in 2019. The cost of hydrogen production using PEM as one of the electrolyser technologies is estimated at US$3.5–US$5.2/kg-H_2, which is a little higher than the expected hydrogen supply cost of US$1–US$2/kg-H_2. Considering a cost reduction in the hydrogen production cost due to strong competition with other countries, such as India and Middle Eastern countries, Brunei will be a continuous energy-exporting country after oil and gas because hydrogen is classified as a clean fuel.

Based on the conclusions mentioned above, the following points are recommended:

a. Brunei Bay could have a large potential for a floating solar PV system.

b. However, blue hydrogen production is a crucial policy for Brunei due to its limited renewable energy resources.

c. The power generation cost of floating solar PV is estimated at US$0.07/kWh, and further cost reductions, such as lower than US$0.05/kWh will be targeted.

d. The green hydrogen production cost using solar PV systems is forecasted to be US$3.5–US$5.2 per kg-H_2 and will be slightly more expensive compared to the expected hydrogen supply cost (US$1–US$2 per kg-H_2). Innovative electrolyser technologies are expected to be available commercially, such as solid oxide electrolytic cell (SOEC) and anion exchange membrane (AEM) technologies.

e. Carbon dioxide enhanced gas recovery and carbon dioxide enhanced oil recovery as CCS should start with collaboration with foreign organisations, such as the Japan Oil, Gas and Metals National Corporation.

f. Hydrogen demand will be huge in Asia, but there will be many competitors (the Middle East and India) for hydrogen exports. Brunei's advantage in terms of hydrogen exports is its location at the centre of Asia, so its hydrogen transport costs will be much lower than its competitors.

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Appendices

Appendix 1. Floating Solar System Costs

The capital costs (CAPEX) of floating PV are slightly higher or comparable to those of ground-mounted PV, owing to the need for floats, moorings, and more resilient electrical components.

Total capital expenditures for turnkey FSPV installations in 2018 generally ranged between US$0.8 and US$1.2 per Wp, depending on the location of the project, the depth of the water body, variations in the depth, and the size of the system.[2]

A rough estimation of the renewable electricity cost for Ulu Tutong Dam is as follows.

Electricity capacity	330 MWp
CAPEX	330 MWp x (0.8–1.2) US$/Wp = US$264 million–US$396 million
Electricity generated	550,000 MWh/y
Years of depreciation	10 years
Electricity cost	(US$264 million–US$396 million) x 0.1/550,000 MWh = <u>0.05~0.07</u> US$/kWh

[2] World Bank Group (2019), *Floating Solar Market Report*.

Appendix 2. Policy and Regulatory Considerations

(1) Regulations and Guidelines for FSPV Installation in Asian Countries

Japan

At the end of 2021, design and construction guidelines for floating solar power generation systems were enacted by the New Energy and Industrial Technology Development Organization (NEDO).[3]

However, the scope of application is limited to systems installed on freshwater bodies, such as lakes, man-made lakes, and reservoirs, etc., where there is no flow.

As a general rule, these guidelines do not apply to equipment installed on the rivers and seas where unique natural conditions such as storm surges and tsunamis are expected to occur.

The guidelines include the following items:

- Preliminary survey
- Structural design and construction planning
- Electrical design and construction planning
- Maintenance plan

In addition, Japan's Ministry of Agriculture, Forestry and Fisheries has issued guidance on the installation of floating PV systems in agricultural reservoirs.[4]

Republic of Korea

Regarding FSPV, there was a restriction in the past that the ratio of the installation area should be within 10% for reservoirs and within 20% for freshwater lakes, but this has now been abolished.

In addition, construction standards for installation on water bodies have been created in the solar construction standards under the jurisdiction of the New and Renewable Energy Center.

Taiwan

Regarding installation on water bodies, the installation area of FSPV is limited to 50% or less of the irrigation reservoir area according to the management principle of the installation of solar power generation equipment.

It is regulated that the water quality should be tested regularly, the water quality standards for irrigation should be met, and the use of detergents that pollute the water should be restricted.

[3] NEDO (2021), *Design and Construction Guidelines for Floating Solar Power Generation Systems* (in Japanese).
[4] Ministry of Agriculture, Forestry and Fisheries (2021), *Guidance on Installation of Floating Solar Power Generation Equipment in Agricultural*, Ponds Rural Development Bureau (in Japanese).

(2) Environmental and Social Aspects of FSPV Systems

Environmental and social aspects specific to the construction and operation of FSPV projects are as follows.

Water quality

FSPV projects may affect water quality to varying degrees, depending on their type and design characteristics. The use or accidental release of oil and/or lubricants from boats used during maintenance activities or detergents used to clean panels can affect water quality and aquatic flora and fauna. Some have argued that FSPVs should not be installed in reservoirs that serve as drinking water sources, and a full safety assessment is required when installing FSPVs in such bodies of water.

In Japan, the installation of FSPV in ponds used for agricultural water is progressing, and it is required to confirm whether the installation of FSPV will deteriorate the quality of stored water. In addition, there are cases where power generation companies are required to conduct water quality inspections of ponds once a year and take necessary measures at their own expense if problems arise in terms of water quality.

FSPV installation permits

In some countries, drinking water reservoirs or hydropower reservoirs are considered national-security sites, making permitting more complex and potentially protracted.

Appendix 3. FSPV Damage Countermeasures

1. Damage by Typhoons

- Kawashima Sun and Nature’s Megumi Solar Park, 7.55 MW, Saitama, Japan

  (1) The mega solar plant started operating on 26 October 2015, and 27,456 solar panels are fixed on floating mounts.
  (2) Kawashima Sun and Nature's Megumi Solar Park was damaged by Typhoon No. 9 on 22 August 2016.
  (3) 152 panels (41.8 kW) and floating racks were damaged by strong winds and high waves.
  (4) Since empty floats without panels on the periphery were not connected, the panels protruded from the float and were easily blown by the wind.

- Chiba Yamakura Floating Mega Solar Power Plant, 13.7 MW, Japan

  (1) On the afternoon of 9 September 2019, when Typhoon No. 15 passed through Chiba Prefecture, a fire broke out at the Chiba Yamakura Floating Mega Solar Power Plant on the surface of Yamakura Dam in Chiba Prefecture.
  (2) Due to the strong winds from the typhoon, the float mounts were damaged so that they were stacked on top of each other.

<u>Countermeasures:</u>

- The floating island (a PV power generation system installed on the water) was simplified and downsized and divided into six parts to prevent a local concentration of power.
- Increased the number of float anchors from 420 to 904 to improve wind safety.
- In order to prevent electric fires, measures such as dividing the electric cables into positive and negative and putting them in protective tubes were taken.

2. Salt Damage for Offshore Installations

It is important to take countermeasures against salt damage when installing FSPV offshore, and countermeasures are summarised in Table A1.

Table A1. Measures Against Salt Damage

Manufacturer	Measure
Sharp	Dedicated modules and mounts are available for each region where salt damage countermeasures are required. Products other than tile type (NT-58K1D, NT-41K1D) are also resistant to heavy salt damage. However, places where seawater directly splashes during strong winds are excluded.
Mitsubishi Electric	Module: In preparation for installation in salt-damage areas, a 3-layer structure back film with excellent weather resistance, moisture residence, and sealing performance is used. Corrosion-resistant plating is used for the frame and screws. Frame: Aluminium that forms an oxide film and clear coat prevent corrosion and salt damage.
Kyocera	Solar cell modules and rack systems can be installed as standard products, even in coastal areas. They cannot be installed in places where seawater, etc. directly splashes. Photovoltaic module: Light receiving surface is made of tempered glass (white plate heat-treated glass); the back surface is a multi-layered film (back sheet) with excellent weather resistance; and the frame is also made of aluminium alloy with various surface treatments (anodised, electrodeposition) applied. The internal solar cells are completely sealed with a thin layer of transparent resin, etc. to protect them from moisture and dust. The connector is also dustproof and waterproof. Rack system: Hot-dip galvanised steel, hot-dip zinc-aluminium-magnesium-coated steel, stainless steel, and aluminium alloy with a similar surface treatment to the frame of solar modules. Power conditioner: Cannot be installed in areas where salt damage is expected within 500 m from the coast.
Canadian Solar	In salt-damage areas (areas not directly exposed to droplets and within 500 m of the coast), a salt-damage stand is required and installation is possible. The solar modules are PID free, salt corrosion resistant, and ammonia resistant. Passed the most rigorous tests for salt corrosion resistance, certified to IEC61701 Ed2 (salt spray test) and IEC60068-2-52 Ed.2 (environmental test severity 1), standards adopted in 2011.
Solar Frontier	Solar Frontier's CIS thin-film solar cells are certified by TUV Rheinland Japan (IEC Standard), under writers Laboratories, and BRE Global (Microgeneration Certification Scheme). They are also certified for resistance to salt and ammonia and can be installed in coastal and agriculture areas.

CIS = copper, indium, and selenium; PID = potential-induced degradation.
Source: Authors.