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A Decarbonization Roadmap for Singapore and Its Energy Policy Implications

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Abstract: As a signatory to the Paris Agreement, Singapore is committed to achieving net-zero carbon emissions in the second half of the century. In this paper, we propose a decarbonization roadmap for Singapore based on an analysis of Singapore's energy landscape and a technology mapping exercise. This roadmap consists of four major components. The first component, which also underpins the other three components, is using centralized post-combustion carbon capture technology to capture and compress CO_2 emitted from multiple industrial sources in Jurong Island. The captured CO_2 is then transported by ship or an existing natural gas pipeline to a neighboring country, where it will be stored permanently in a subsurface reservoir. Important to the success of this first-of-a-kind cross-border carbon capture and storage (CCS) project is the establishment of a regional CCS corridor, which makes use of economies of scale to reduce the cost of CO_2 capture, transport, and injection. The second component of the roadmap is the production of hydrogen in a methane steam reforming plant which is integrated with the carbon capture plant. The third component is the modernizing of the refining sector by introducing biorefineries, increasing output to petrochemical plants, and employing post-combustion carbon capture. The fourth component is refueling the transport sector by introducing electric and hydrogen fuel cell vehicles, using biofuels for aviation and hydrogen for marine vessels. The implications of this roadmap on Singapore's energy policies are also discussed.

Keywords: decarbonization; roadmap; Singapore

Citation: Lau, H.C.; Ramakrishna, S.; Zhang, K.; Hameed, M.Z.S. A Decarbonization Roadmap for Singapore and Its Energy Policy Implications. *Energies* **2021**, *14*, 6455. https://doi.org/10.3390/en14206455

Academic Editor: Federica Raganti, Paola Ammendola, Rocio Maceiras

Received: 31 August 2021
Accepted: 29 September 2021
Published: 9 October 2021

1. Introduction

Climate change brought about by global warming is an existential problem facing Singapore. The following are some examples of how climate change is affecting Singapore [1]. Between 1980 and 2020, the annual mean temperature in Singapore has increased from 26.9 °C to 28.0 °C. This temperature rise could lead to more occurrences of warm-weather diseases such as dengue fever, as well as heat stress and discomfort among the elderly and sick. It also puts Singapore's plants and animals at risk as it alters the natural processes in the ecosystem such as soil formation, nutrient storage, and pollutant absorption. In addition, the mean sea level in the Straits of Singapore increased at a rate of 1.2 to 1.7 mm per year between 1975 and 2009. This sea level rise poses an immediate threat to Singapore, as much of the nation lies only 15 m above sea level, whereas 30% of the country is less than 5 m above sea level. Furthermore, the annual rainfall for Singapore increased at an average rate of 6.7 cm per decade from 1980 to 2019, posing significant challenges to the country's water resources. An increase in the intensity of weather variability, such as drought and intense rainfall, could overwhelm the nation's drainage system, leading to flash floods, as well as adversely affecting global food security.

Many scientists believe that the global warming is brought about by an increase in anthropogenic CO_2 emissions, which blocks the irradiation of heat to outer space due to the greenhouse effect [2,3]. Since the signing of the Paris Agreement in 2015, most nations have established targets to reduce greenhouse gas emissions. The overall goal is to reduce the global temperature rise to less than 2 °C and preferably less than 1.5 °C compared to pre-industrial times. This will mean achieving net-zero greenhouse gas emission for most nations by 2050 or shortly afterwards. As a signatory to the Paris Agreement, Singapore is committed to achieving net-zero emissions in the second half of the century.

2. Purpose and Methodology of Study

The purpose of this study is to propose, for the first time, a high-level roadmap for Singapore to achieve net-zero emissions before the end of the century. Based on an analysis of Singapore's energy landscape and the impact and readiness level of various decarbonization technologies in the context of Singapore, this roadmap points out the major levers for decarbonization wherein concerted efforts can make the biggest difference. Concomitantly, we suggest policies relevant for the implementation of this roadmap.

Our methodology is three-fold. First, we analyze the energy landscape of Singapore. Second, we conduct a technology mapping exercise to identify the mature technologies that have the most impact on reducing Singapore's CO_2 emission. Third, we propose a decarbonization plan based on this technology mapping. Finally, we draw energy policy implications resulting from this roadmap.

3. Singapore's Decarbonization Commitment

In 2017, Singapore emitted 52 million tons of CO_2, which was 0.1% of global emissions [1]. Singapore ranks 27th out of 142 nations in terms of per capita CO_2 emissions and 126th in terms of CO_2 emissions per dollar of GDP. As a signatory to the Paris Agreement, Singapore has pledged to achieve peak CO_2 emissions of less than 65 million tons by 2030, halve it by 2050, and reduce it to zero before 2100 [4]. Figure 1 gives the historical CO_2 emissions from Singapore. It also shows the projected CO_2 emissions required to achieve net-zero by 2080. Between 2030 and 2080, a very sharp declining rate in CO_2 emission will be needed to realize the goal of net-zero before the end of the century. Figure 2 shows the primary and secondary CO_2 emission from Singapore in 2017. The three sectors emitting most CO_2 were power (39%), industry (46%) and transport (13%). Within the industry sector, most of the emission came from refineries.

In this paper, we propose a roadmap to achieve this net-zero timetable. This roadmap consists of four parts: (1) CCS, (2) hydrogen production, (3) modernizing the refining sector, and (4) using low-carbon fuels for the transport sector. Figure 1 illustrates a future scenario in which CCS will contribute to 59% of the reduction in CO_2 emissions, hydrogen and modernization of the refining sector will contribute to 24%, and the use of low-carbon fuels in transport will contribute to 12%. Although other scenarios are possible, we expect CCS will play a major role in the overall decarbonization effort.

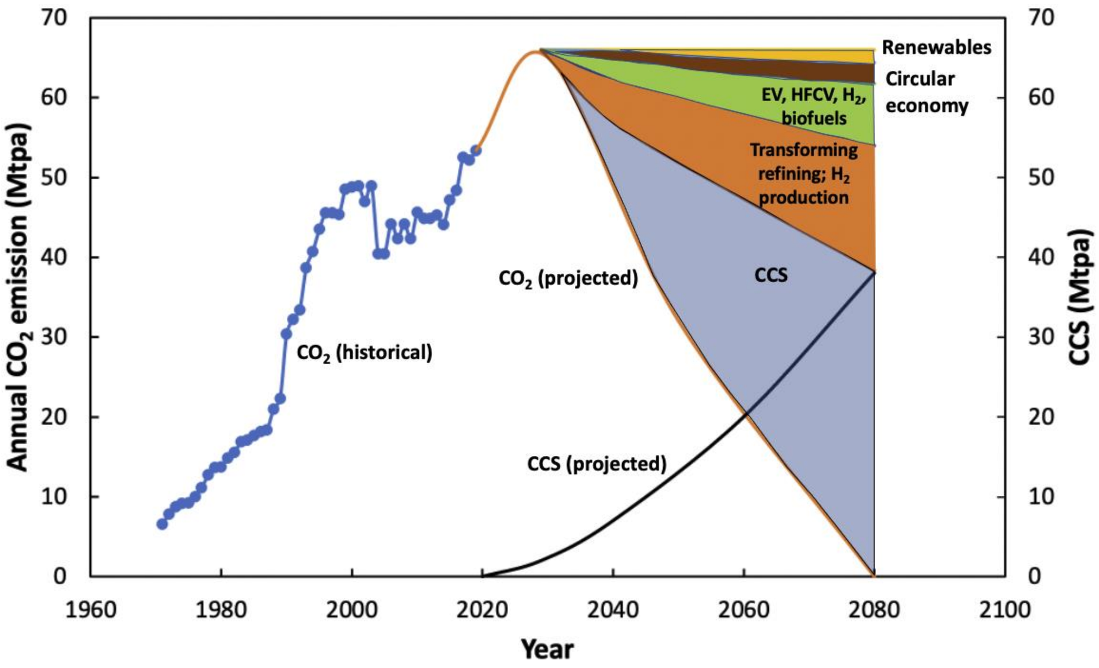


Figure 1. Singapore's CO_2 emissions and illustrative reductions needed to achieve net-zero emissions by 2080.

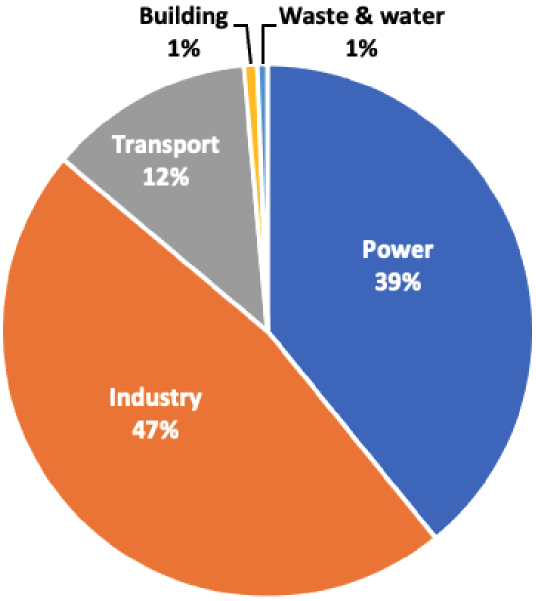


Figure 2. Singapore's CO_2 emission in 2018.

4. Singapore's Energy Landscape

There are four unique features of Singapore's energy landscape, which must be considered in the design of an energy transition roadmap.

First, being a nation state with only an area 728 km^2, Singapore lacks its own fossil fuel or renewable energy resources. Consequently, 98% of Singapore's demand comes from imported fossil fuels, mainly oil and natural gas. In 2019, 86% of Singapore's primary energy consumption came from imported oil, 13% from imported natural gas, and only 0.24% from domestic solar PVs and other renewables [5].

Second, by design, Singapore's CO_2 emissions are highly concentrated on two small islands: Jurong and Bukom (Figure 3a). Jurong Island, 32 km^2 in area, is home to most of Singapore's refining, petrochemical, and power plants. Bukom Island, 1.45 km^2 in area and located just 4 km east of Jurong Island, is home to Shell's biggest refinery. Jurong

Island is responsible for over 50% of Singapore's CO_2 emissions, thus making it a prime target for carbon capture (Figure 3b).

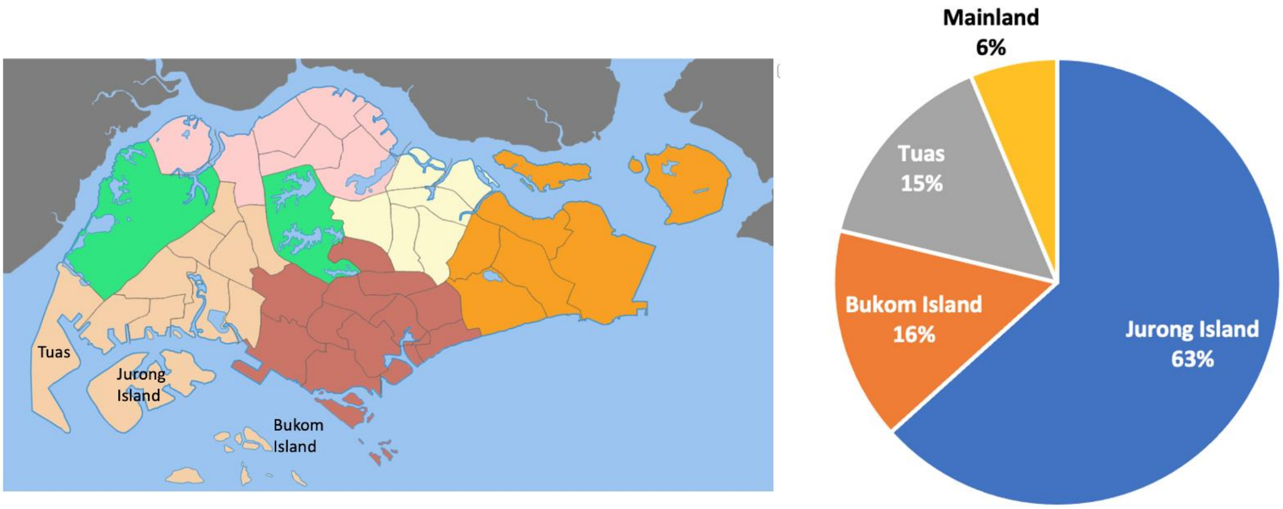
Third, Singapore's industry sector is heavily concentrated in refining and petrochemicals, which are highly integrated to improve their efficiency. Together, they account for most Singapore's industrial CO_2 emissions [6], with the refining sector being the biggest CO_2 emitter. Singapore has the world's fifth largest oil refining capacity of 1.5 million bbl/d in 2018 [7].

Fourth, being at the center of southeast Asia, Singapore is close to many CO_2 subsurface storage sites, such as saline aquifers, as well as oil and gas reservoirs. Although Singapore lacks subsurface storage sites for CO_2, there are plenty of them within a 1000 km radius of Singapore. This fact creates unique opportunities for the implementation of a cross-border CCS project.

Singapore's Emission Profile

Out of Singapore's total CO_2 emissions, 47% comes from industry, 39% from power generation, 12% from transport, and 2% from buildings and other sectors (Figure 2) [4]. However, practically all the emissions from industry sector come from the refining and petrochemical sectors.

One unique feature of Singapore's stationary CO_2 emissions is that 62% of them come from Jurong Island, which is a small island with an area of 32 km^2 located in the southwest of Singapore (Figure 3a). About 71% of Singapore's power plants, 69% of refineries, and practically all petrochemical and chemical plants are in Jurong Island. It is home to some of the largest refineries and petrochemical complexes in Southeast Asia. Refineries in Jurong Island and Bukom Island process 1.5 million bbl/d, turning crude oil into gasoline, kerosene, diesel, and jet fuel that is sold domestically and abroad. Jurong Island's petrochemical plants rank among the top 10 in the world and produce lubricants, resins, polymers, plastics, and fuel additives. In 2015, Jurong Island contributed to SGD 81 billion or one-third of Singapore's total manufacturing output [8]. Due to this concentration of industries, 54% of Singapore's total CO_2 emissions, or 27 million tons per year, comes from Jurong Island. This creates a unique opportunity for centralized post-combustion carbon capture and processing.



(a) (b)

Figure 3. (**a**) Map of Singapore, (**b**) CO_2 emissions from industry and power by location.

5. Technology Mapping

Figure 4 and Table 1 present the results of a technology mapping exercise based on two criteria: technology impact and technology readiness in Singapore. In this exercise, renewable energies such as wind, hydroelectricity, geothermal, and solar thermal energy are ranked low because of their unavailability. Carbon capture and utilization (CCU) has a medium level of technology readiness and impact. Most CCU technologies are in the pilot stage and their potential to mitigate large quantities of industrial CO_2 is low to medium. Both hydrogen fuel cell vehicles (HFCV) and green hydrogen have very high impact on reducing Singapore's CO_2 emissions. However, their technology readiness level is low to medium. Importing electricity through the regional grid and constructing zero-emissions buildings both have high technology readiness levels. However, their impact on CO_2 mitigation is medium to low. There are six technologies ranked as having a high impact and high readiness level. They are CCS, biofuels, solar PVs, blue hydrogen, electric vehicles (EVs) and the adoption of a circular economy. Out of these, biofuels, solar PVs, EVs and a circular economy are already present in Singapore. CCS and blue hydrogen have yet to be implemented in Singapore.

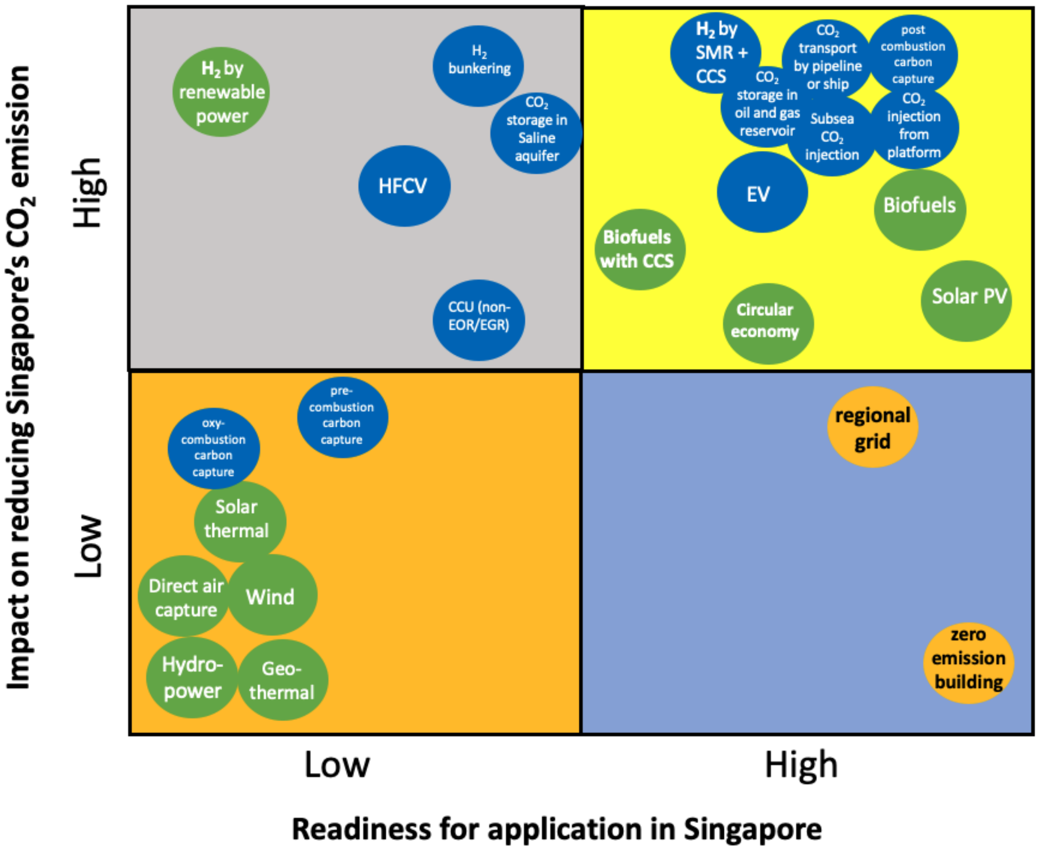


Figure 4. Technology mapping for decarbonizing Singapore.

Table 1. Ranking of the impact and readiness of various technologies on the decarbonization of Singapore.

Technology	Impact on Singapore's CO_2 Emission	Readiness for Application in Singapore	Comment	Reference
Post-combustion carbon capture	High. Capturing CO_2 from existing power plants, refineries, and chemical plants.	High. Post-combustion carbon capture technology with amines is mature.	Centralized post-combustion carbon capture in Jurong Island to take advantage of economies of scale.	[9,10]

Pre-combustion carbon capture	Medium. Used only for new plants. Potential integration with hydrogen production.	Low. Not cost competitive with post-combustion carbon capture in NGCC due to the high cost of syngas generation.	Difficult to apply in Singapore's integrated refinery-petrochemical complex.	[11]
Oxy-combustion carbon capture	Low. Used only for new plants.	Low. Not cost-competitive with post-combustion carbon capture in NGCC because of costly air separation unit.	Difficult to apply in Singapore's integrated refinery-petrochemical complex.	[10,12]
CO_2 transport by pipeline	High. Capable of transporting large quantities of CO_2 at low cost.	High. CO_2 can be shipped as supercritical fluid in pipelines. Uses existing trans-ASEAN gas pipelines.	Two existing natural gas pipelines connect Singapore to Indonesia. One or both may be used for CO_2 transport in 2023.	[13]
CO_2 transport by ship	High. Capable of transporting large quantities of CO_2 over long distances.	High. Liquid CO_2 can be shipped by LPG tankers.	Capitalize on Singapore's marine industry. Modify existing LNG terminals to handle liquid CO_2.	[14–16]
CO_2 injection from a platform well	High. Capable of injecting large quantities of CO_2.	High. Many existing offshore platforms in the region.	CO_2 "Huff-n-puff" system in Rang Dong oilfield in Vietnam.	[17]
CO_2 injection from a subsea well	High. Capable of injecting large quantities of CO_2.	High. Significant experience with subsea wells in the region, including Malampaya in Philippines, Gumusut-Kakap and Rotan in Malaysia and West Seno in Indonesia.	Significant subsea well experience in Malaysia and Indonesia.	[18,19]
CO_2 storage in a saline aquifer	High. Very large CO_2 storage capacity, possibly exceeding 100 Gt.	Medium. Detailed characterization of saline aquifers in the region is lacking.	Choice of aquifers awaits subsurface characterization.	[20]
CO_2 storage in an oil reservoir	High. Adequate for many years of CO_2 storage.	High. Many oil reservoirs within 1000 km from Singapore	Potential oilfields for CO_2-EOR in South Sumatra.	[21,22]
CO_2 storage in a gas reservoir	High. Adequate for many years of CO_2 storage.	High. Many gas reservoirs within 1000 km from Singapore	Repsol to pilot CCS in Dayung gas field in South Sumatra.	[23]
Hydrogen production by SMR with CCS	High. The hydrogen industry may become growth engine for economy.	High. Mature technology.	May be considered as part of the modernization of the refining sector.	[24,25]
Electric vehicles	High. The electrification of cars transfers mobile emission to stationary emission which can be removed by CCS.	High. EVs are ideal for Singapore, where driving distances are short.	Singapore will be phasing out internal combustion cars by 2040.	[26]
Biofuels	High. Biofuels may be used for cars, ship, and aviation.	High. One biorefinery in Singapore converts used cooking oil and food waste to renewable jet fuel for North American and European markets.	Singapore already has a biorefinery with a capacity of 1 Mtpa. There is a plan to expand it to 1.3 Mtpa.	[27]
Solar PV	Moderate. Solar PV constitutes less than 1% of Singapore's energy mix.	High. Used on rooftops of apartment buildings in Singapore.	There is a plan to increase solar PV capacity from 350 MW to 2 GW by 2030.	[28]
Regional power grid	Moderate	High. There is a plan to construct an ASEAN power grid.	There is a plan to import 100 MW of low-carbon electricity from Malaysia for 2 years.	[29]

Zero-emissions buildings	Moderate	High. Singapore launched the first zero-emissions building in Southeast Asia powered by green hydrogen in 2019.	National University of Singapore launched Singapore's first zero-emission building powered by solar PV in 2019.	[30,31]
Circular economy	Moderate. Singapore's domestic and overall recycling rate was 17% and 52%, respectively in 2020.	High. Singapore issued its Zero Waste Masterplan in 2019.	Singapore plans to reduce waste sent to Semakau Landfill by 30% by 2030.	[32,33]
Green hydrogen by renewable electricity	High. Green H_2 eliminates most CO_2 emissions.	Low. No commercial-scale green H_2 production in Singapore. Purchase from overseas possible but costly.	Within Asia, Japan has announced plans to import hydrogen, whereas Australia plans to export hydrogen. South Korea and New Zealand have published their goals for a hydrogen economy.	[34–37]
Hydrogen fuel cell vehicles	High. HFCVs will eliminate mobile CO_2 emission from vehicles.	Moderate. Currently, Singapore has no H_2 infrastructure. However, development is possible due to its small area.	Despite no government policy favoring HFCVs, one local company plans to make HFCVs.	[38]
Hydrogen bunkering for ships	High. As a bunkering center for ships, Singapore can benefit from H_2 bunkering for zero-emissions ships.	Moderate. Singapore has no hydrogen production for transport. However, development is possible as part of industry modernization.	Singapore signed an SGD 23 million deal with Australia to develop maritime hydrogen. Shell is to trial hydrogen fuel cell for ships in Singapore.	[39,40]
Carbon capture and utilization (Non EOR/EGR)	Moderate. The utilization of CO_2-based chemicals is small compared to CO_2-based fuels. Both are under R&D.	Moderate. Most CCU technologies are in the R&D stage and are not commercial.	CO_2-based fuels such as methane and methanol are not cost-competitive and require breakthroughs in catalysis technology.	[41]
Solar thermal	Low	Low. Limited roof space for solar thermal installation in Singapore's buildings. May be seen as competition to solar PV.	Space heating not in demand due to Singapore's hot climate.	[42]
Wind energy	Low	Low. Wind speed around Singapore is too low for wind turbine.	Inadequate land and sea space for wind turbines.	[43]
Hydroelectricity	Low	Low. Singapore lacks river for hydroelectricity.	Singapore can invest in hydroelectricity in Laos and use renewable energy credits to import electricity from Malaysia.	[44]
Geothermal energy	Low	Low. No geothermal resources in Singapore.	Geothermal energy in SE Asia resides mainly in Indonesia and Philippines.	[45]
Direct air capture	Low	Low. Technology not commercial.	Global DAC capacity is 9000 tons/y, mostly in US	[46,47]

6. Decarbonization Roadmap

Based on the aforementioned technology-mapping exercise, we propose a decarbonization roadmap for Singapore. It consists of four key components: (1) CCS, (2) hydrogen production, (3) transforming refining, and (4) refueling transport (Figure 5).

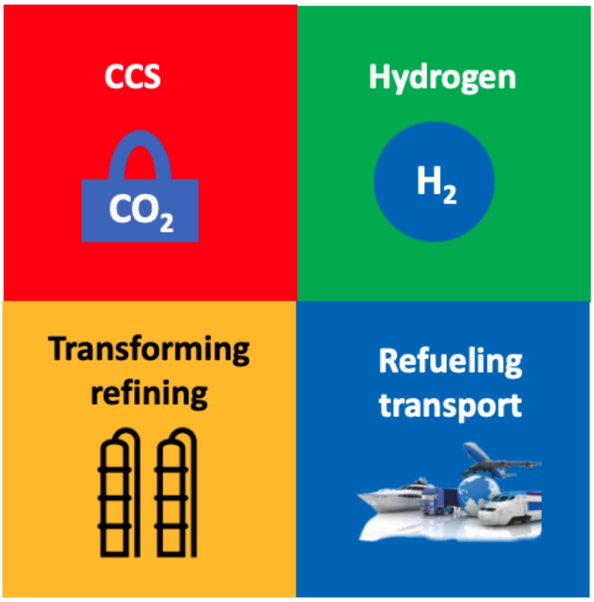


Figure 5. Four components of the decarbonization roadmap.

Of the four components, CCS is fundamental because it underpins the other three. We propose using centralized post-combustion carbon capture to capture the CO_2 emitted from the power, refining, and petrochemical industries located in Jurong Island. The second component is hydrogen manufacturing using a steam methane reforming (SMR) plant and integrating it with the carbon capture plant in Jurong Island. The third component is transforming the refining industry in Singapore by a readjustment of output, the incorporation of biorefineries, and the use of post combustion CCS. The fourth component consists of replacing existing internal combustion engine cars with electric vehicles and hydrogen fuel cell vehicles, using biofuels for aviation and hydrogen for marine vessels. Key elements of this roadmap are shown in Figure 6.

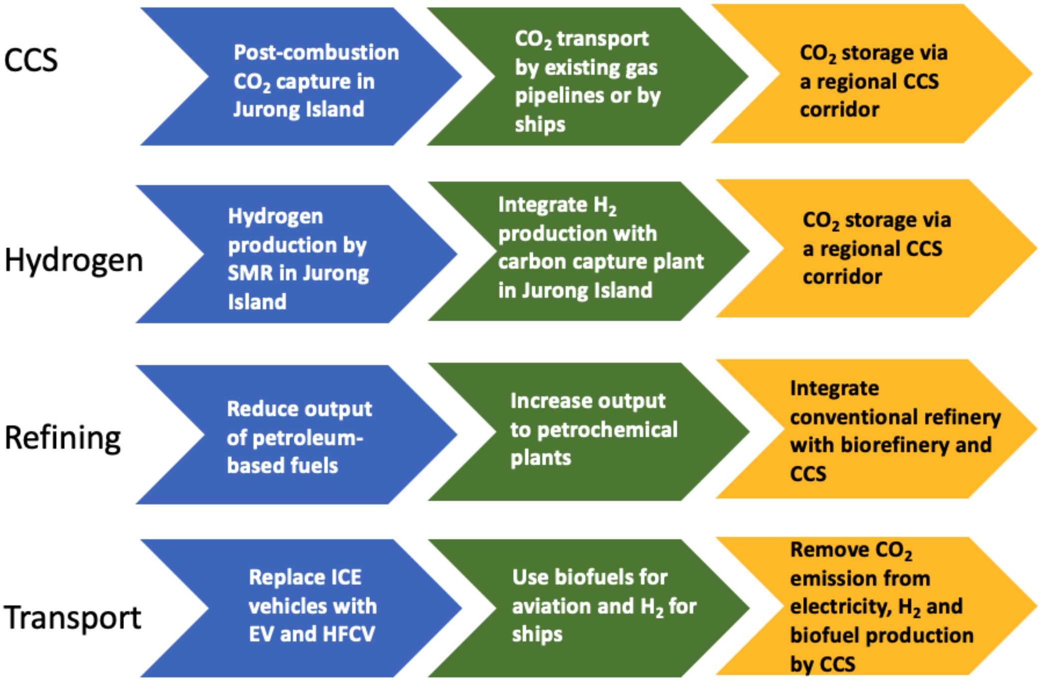


Figure 6. Key elements of the decarbonization roadmap.

According to our roadmap, post-combustion carbon capture will be the main method used to mitigate CO_2 emission. One possible scenario in our roadmap is given in Figure 1, wherein 59% of the reductions will be achieved by CCS; 24% by reducing refinery output and industry restructuring; and 12% by fueling transport using electricity, hydrogen, and biofuels. Achieving this will require ramping up CCS from zero to 38 Mtpa between now and 2080. This is feasible if an ASEAN open-access CCS corridor is established in the next decade. Other scenarios, for example using CO_2 to produce building materials and chemicals, are possible. However, regardless of which scenario is chosen, CCS will be the major contributor to Singapore's decarbonization. Table 2 summarizes the main CO_2 mitigation methods by sector resulting from our technology mapping exercise.

Table 2. CO_2 mitigation method by sector.

Sector	CO_2 Mitigation Method
Power	Post-combustion CCS More solar PV Importing electricity from regional grids Hydrogen for power generation
Refining	Reduce output of petroleum-based fuels Increase output to petrochemical plants Incorporate and integrate with biorefineries Post-combustion CCS
Petrochemical	Post-combustion CCS Hydrogen for heat and as feedstock
Transport	Replacing passenger cars by EV Replacing buses and heavy vehicles by HFCV Biofuels for aviation Hydrogen for ships
Building and others	Zero-emissions buildings Adoption of a circular economy

6.1. Carbon Capture and Storage (CCS)

Carbon capture and storage is the foundation stone of the proposed roadmap as it is the only mature technology that allows Singapore to remove the millions of tons of emitted CO_2 per year needed to achieve net-zero before the end of the century.

6.1.1. Centralized Post-Combustion CO_2 Capture

Due to a high concentration of large CO_2 emitters in Jurong Island (Figure 7), it is possible to direct flue gas from multiple industrial plants to a central location for carbon capture and compression. Post-combustion carbon capture technology may be used to capture CO_2 from several flue gas streams with varying CO_2 concentrations. Our analysis shows that in Jurong Island, the CO_2 concentration in the flue gas is 15%–25% from power plants, 30%–45% from refineries, and 40%–80% from petrochemical plants. The pressure of these flue gas streams may be boosted by a vapor recovery compressor, allowing them to be pumped to a centralized plant for CO_2 capture. In this plant, CO_2 may be absorbed by liquid solvents such as MDEA, MEA, DEA, and NaOH. The solvent can be regenerated by stripping the CO_2 out of the liquid by steam. The regenerated solvent can be returned to the absorber column while a concentrated CO_2 stream is produced. In addition to chemical solvents, solid absorbents, membranes, or a combination of them may also be used for post-combustion CO_2 capture. After being captured, CO_2 can be compressed and cooled to liquid or supercritical form. Although post-combustion carbon capture can be retrofitted into existing industrial plants, it is cheaper to build a single centralized plant to capture CO_2 from multiple sources. Our roadmap calls for the building of a plant that has the capacity to capture 5 Mtpa of CO_2, which is on par with the largest post-combustion carbon capture plants in the world [48]. By integrating CO_2 capture, liquefaction, and temporary storage into a single centralized plant, a greater reduction in capital investment can be achieved. Centralized post-combustion carbon capture is only possible due to Singapore's unique CO_2 emissions profile. A centralized post-combustion CO_2 capture plant in Jurong Island capable of processing several million tons of CO_2 per year will be a first-of-a-kind project in the world.

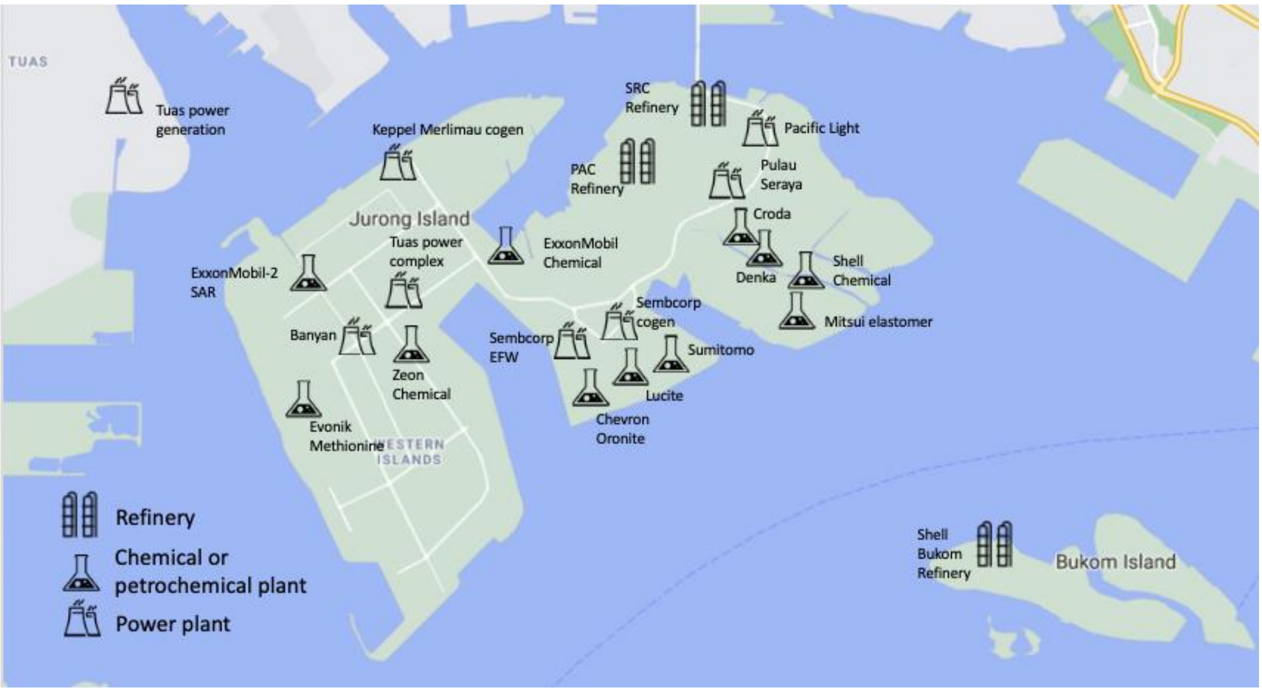


Figure 7. Major power plants, refineries, and chemical/petrochemical plants in Jurong and Bukom Islands.

6.1.2. CO_2 Transportation from Singapore

CO_2 is usually transported in a supercritical form by pipelines or in liquid form by marine vessels [14]. In pipeline transport, the pipeline is usually pressurized to above 10.3 MPa to ensure that CO_2 is in a supercritical form with a density close to 800 kg/m^3 and a viscosity close to 0.8 cp. Therefore, the pressure drop in a pipeline can be readily estimated. Over long distances, booster stations may be needed to keep the CO_2 in the supercritical phase. There are two existing pipelines supplying natural gas to Singapore from Indonesia. One of them is the 654-km-long West Natuna–Singapore pipeline that supplies natural gas from Indonesia's West Natuna gas field to Jurong Island (Figure 8). The gas delivery contract for this pipeline will end in 2022 and it is not certain whether it will be renewed. The second is the 470-km-long South Sumatra–Singapore pipeline that supplies natural gas from Indonesia's Suban gas field in South Sumatra to Singapore (Figure 8). This pipeline will cease to operate by 2023, when the existing gas contract ends. Indonesia plans to use the gas for domestic consumption. If one or both of these pipelines cease to be used for natural gas delivery, they may be used instead for shipping CO_2 from Singapore to subsurface reservoirs in either South Sumatra or the West Natuna Basin for permanent storage. In addition, Singapore's gas transmission network is connected to Petronas' Peninsula Gas Utilization Pipeline. This network was used to supply natural gas from Malaysia to Singapore. These existing natural gas pipelines may be used to transport industrial CO_2 from Singapore to Indonesian or Malaysian subsurface reservoirs for permanent storage. In such a scenario, the shipment of CO_2 from Singapore will be relatively inexpensive as no or limited new pipelines need to be constructed. If existing natural gas pipelines cannot be used, the building of a new CO_2 pipeline to the nearest sink may also be considered. It should be noted that there are over 3000 km of CO_2 pipelines in the world, moving many tens of million tons of CO_2 annually. For the transportation of CO_2 over long distances, where existing pipelines are unavailable, marine shipments can be used. Currently, small quantities (a capacity of 1000 m^3) of liquefied CO_2 is being transported by ships by the food and beverage and chemical industries. Marine shipments of large quantities of CO_2 can be undertaken by LPG tankers with a capacity of 100,000 m^3 (80,000 tons) of liquid CO_2. The existing LNG terminal in Jurong Island may be modified to handle the offloading of liquid CO_2. As Singapore is a hub for ship building, modifying LPG tankers or building new tankers for liquid CO_2 shipments in Singapore's shipyards is feasible. The cross-border movement and storage of CO_2 will require risk assessments and government-to-government negotiations (See Section 7.1.6).

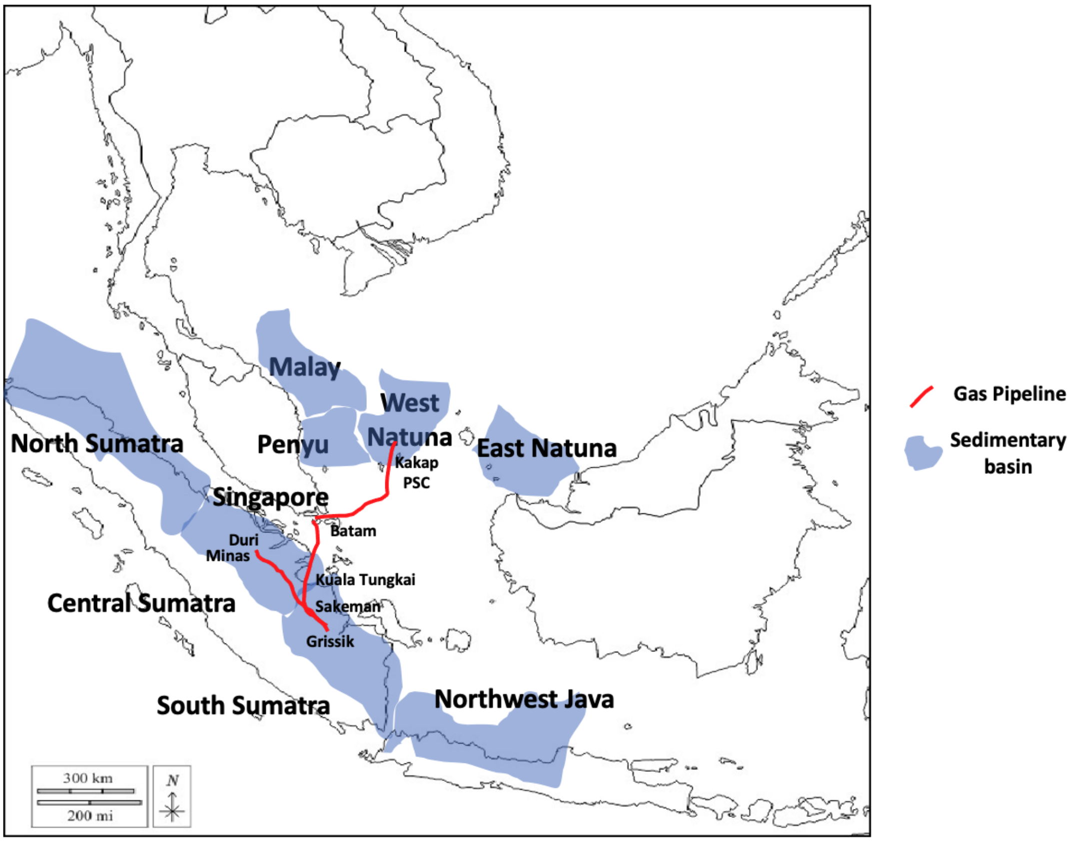


Figure 8. Natural gas pipelines supplying gas to Singapore from West Natuna field and Grissik field.

6.1.3. CO_2 Storage Using a Regional CCS Corridor

An important part of the roadmap is a detailed CO_2 source-sink mapping exercise to identify large industrial CO_2 sources and subsurface reservoirs for permanent CO_2 storage [49]. Initially, such a source-sink mapping exercise should identify CO_2 sources and sinks within a 1000 km radius from Singapore (Figure 9). Besides Jurong Island in Singapore, large stationary CO_2 sources within this area include power plants, refineries, and factories in Sumatra, Northwest Java, and Peninsula Malaysia. It is interesting to note that four (North Sumatra, Riau, Lampung, South Sumatra) of the top provinces for CO_2 emissions in Indonesia are located in the Sumatra Island. There have been previous studies on the potential of CCS potential in the region [50–52].

Major CO_2 sinks are subsurface layers of porous media (reservoirs), which include saline aquifers as well as depleted or partially depleted oil and gas reservoirs [53].

There are eight major sedimentary basins within a 1000 km radius from Singapore (Figure 1). They are the North Sumatra, Central Sumatra, South Sumatra, Northwest Java, East Natuna, West Natuna, Penyu, and Malay basins. The first six basins are in Indonesia, whereas the last two are in Malaysia. There are many oil and gas reservoirs of varying degrees of depletion in these eight sedimentary basins (Tables 3 and 4). Our preliminary estimates show that the total CO_2 storage capacity in these seven basins exceeds 100 Gt, of which 90% resides in saline aquifers and the remaining in oil and gas reservoirs [22,51]. It should be noted that the injection of CO_2 into an oil or gas reservoir may lead to the production of incremental oil or gas by processes known as enhanced oil recovery (EOR) or enhanced gas recovery (EGR) due to the total or partial miscibility of the CO_2 with the oil or gas condensate in the reservoir [49]. This makes the economics of CO_2-EOR or EGR more attractive than the pure geological storage of CO_2 in a saline aquifer.

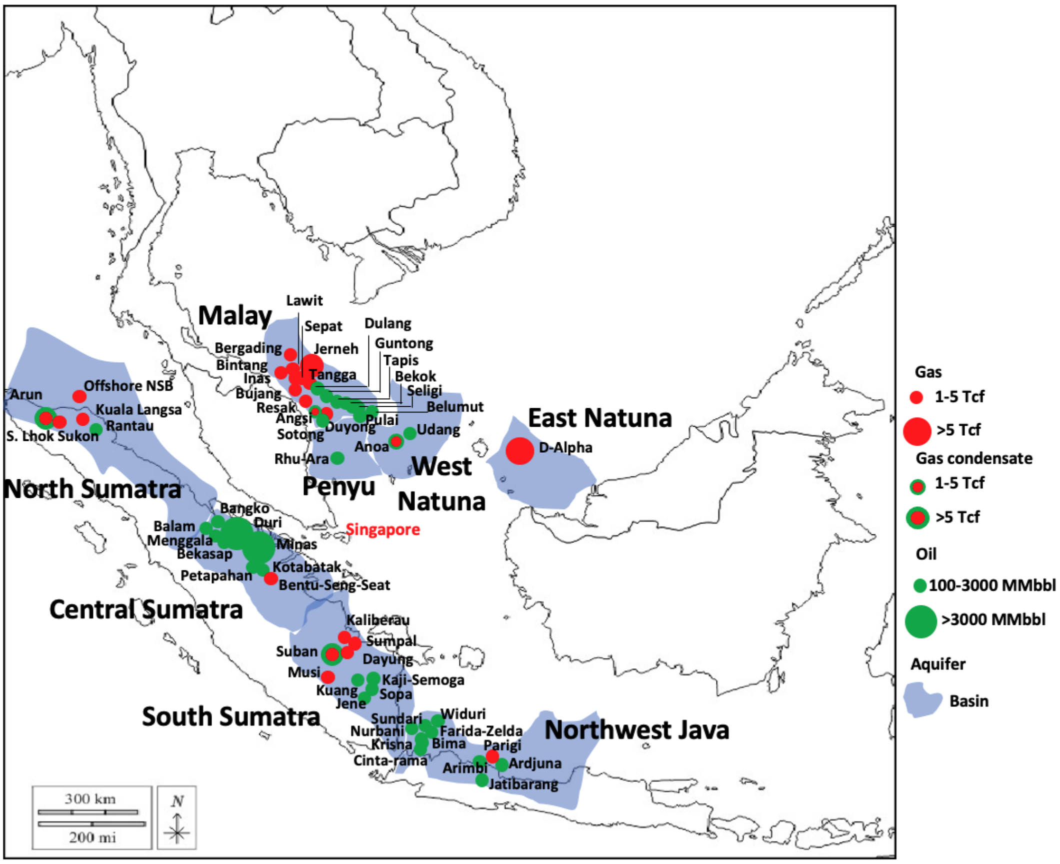


Figure 9. Sedimentary basins and oil and gas fields within 1000 km from Singapore.

Table 3. Major Indonesian reservoirs within 1000 km from Singapore.

Basin	Distance to Singapore (km)	Oil Field (OOIP > 100 MMbbl)	Gas Field (OGIP > 1 Tcf)	Saline Aquifer
North Sumatra	890		Arun *	Various
	800		Kuala Langsa	
	860		S. Lhok Sukon	
	810		Offshore NSB	
	740	Rantau		
Central Sumatra	210		Bentu-Seng-Seat	Various
	270	Duri		
	200	Minas		
	310	Bangko		
	260	Bekasap		

	310	Mengala		
	300	Balam		
	230	Petapahan		
	210	Kotabatak		
	270	North Pulai		
South Sumatra	400		Kaliberau	Various
	410		Dayung	
	440		Suban *	
	350		Sumpal	
	440		Musi	
	440	Kuang		
	470	Kaji-Semoga		
	500	Sopa		
	510	Jene		
NW Java	850		Parigi	Various
	740	Cinta-ama		
	720	Krisna		
	670	Widuri		
	720	Bima		
	690	Farida-Zelda		
	650	Sundari		
	650	Nurbani		
	890	Ardjuna		
	830	Arimbi		
	900	Jatibarang		
West Natuna	360		Anoa *	
	400	Udang		
East Natuna	690		D-Alpha	Various

* Gas condensate field.

Table 4. Major Malaysian fields within 1000 km from Singapore.

Basin	Distance to Singapore (km)	Oil Field (OOIP > 100 MMbbl)	Gas Field (OGIP > 1 Tcf)	Saline Aquifer
Malay	350		Angsi *	Various
	350		Duyong	
	510		Jerneh	
	510		Lawit	
	400		Resak	
	500		Bintang	
	500		Tangga	
	430		Bujang	
	390	Seligi		
	400	Tapis		
	380	Pulai		
	390	Bekok		
	420	Guntong		
	390	Sotong		
	390	Belumut		
	440	Dulang		
Pengyu	230	Ruh-Ara		Various

* Gas condensate field.

Detailed regional source-sink mapping will involve ranking CO_2 emission sources by amount and CO_2 concentration. Likewise, CO_2 sinks are ranked by their storage capacity, reservoir type, and readiness for CO_2 storage. The mapping of potential sources to potential sinks is carried out based on factors such as distance, capacity, and readiness [49].

6.1.4. CO_2 Storage in Subsurface Reservoirs

CO_2 can be sequestered in subsurface reservoirs such as saline aquifers, oil reservoirs, gas reservoirs, coalbed methane, geothermal reservoirs, organic-rich shale, gas hydrate reservoirs, and basalt formations [53]. However, the majority of CO_2 storage capacity resides in saline aquifers (over 95%) and oil and gas reservoirs (1%–2%). In Southeast Asia, oil and gas reservoirs have been well studied and characterized by oil companies. CO_2 can be injected into a partially depleted light oil reservoir for enhanced oil recovery, wherein the injected CO_2 is miscible or partially miscible with the oil, thus allowing incremental oil to be produced. This type of CO_2 enhanced oil recovery (EOR) is well understood and has been conducted in the Permian Basin of Texas for over four decades using naturally sourced CO_2 [54]. The chief factor determining CO_2 miscibility is the density of the crude and the reservoir pressure. The reservoir pressure must be above the minimum miscibility pressure (MMP) for CO_2 to be miscible with the crude. Hitherto, CO_2-EOR has not been applied on a commercial scale in Southeast Asia partly because of a lack of stable supply of CO_2. This can change if a constant supply of CO_2 from a large-scale CCS project is implemented in the region. Currently, several CCS pilots are being planned in the region.

In gas condensate reservoirs, a significant amount of condensate or light oil may remain in the reservoir after gas depletion. In such cases, the injection of CO_2 which becomes miscible with the condensate may allow a significant portion of the condensate to be produced [53]. This type of enhanced gas recovery (EGR) can be used for both gas recovery and CO_2 storage.

Both CO_2-EOR and CO_2-EGR are profitable at a medium-to-high oil price, i.e., above $ 50/bbl [55]. However, the fluctuation of the oil price makes it difficult to plan for a long-term CO_2-EOR or CO_2-EGR process. Consequently, government policies that incentivize companies to sequester CO_2 will be highly helpful. A good example is the 45Q tax credit in the US, which gives a tax credit of $35/ton CO_2 sequestered in an oil or gas reservoir and $50/ton CO_2 sequestered in a saline aquifer.

A depleted gas reservoir is also a very good candidate for CO_2 storage. Pore space made available by the produced gas can be used for CO_2 storage. CO_2 can be continuously injected into a depleted gas reservoir until the reservoir pressure reaches the fracture pressure of the reservoir. Depending on the size of the OGIP, the amount of CO_2 stored can be substantial if the CO_2 density under the original conditions is high.

Saline aquifers provide the biggest storage capacity for CO_2 and they are present in practically all sedimentary basins. However, the detailed characterization of saline aquifers is lacking as they are not targets for oil and gas exploration and production. In addition, the geological storage of CO_2 in saline aquifers will not be economically attractive unless there is a substantial carbon tax or credit, which is lacking in Southeast Asia.

Due to their abundance in some Southeast Asia countries, geothermal reservoirs should also be investigated for CO_2 storage. Both Indonesia and the Philippines reside within the Ring of Fire region, known for its geothermal activity. Both countries have substantial hydrothermal reservoirs, as well as hot oil and gas reservoirs. Large amounts of CO_2 may be used as heat transfer fluids for mining the geothermal heat for geothermal power production [53].

The risk of CO_2 leakage during storage in subsurface reservoirs has been well studied in the literature [53]. Leakage is usually due to poorly cemented wellbore, incompetent reservoir seals, or activated faults. Consequently, continuous monitoring of CO_2 plumes by observation wells, seismic methods, and other methods is needed. In general, CO_2 leakage is not a problem if the aforementioned issues are addressed, as demonstrated by many years of field experience in CO_2-EOR in US and CO_2 sequestration projects and Norway [53].

6.1.5. Development Concepts for CO_2 Injection

The development concepts for CO_2 injection are shown in Figure 10. CO_2 may be stored in a reservoir located either onshore or offshore. Most likely, CO_2 transported from industrial sources in multiple countries will be temporarily stored in a coastal facility in the host country for permanent storage (Figure 11). If the CO_2 injection site is onshore, then CO_2 will be transported to that site by pipelines. This is the "beach-to-field" development concept. If the CO_2 injection site is offshore, then CO_2 may be injected into a well in an existing oil or gas platform or into a subsea well. If CO_2 is transported from a beach to an offshore platform by a pipeline, the concept is called "beach-to-platform." If CO_2 is transported to the platform by a marine vessel, this concept is called "ship-to-platform". If CO_2 injection is performed via a subsea well, and CO_2 is transported from the shore to the subsea wellhead by a subsea pipeline, this is known as the "beach-to-subsea" concept. If CO_2 is transported by a marine vessel to a floating buoy through which it is injected into a subsea well, the concept is called "ship-to-subsea." Hitherto, onshore CO_2 injection has been carried out in west Texas [54], and the beach-to-subsea concept has been employed in the Norwegian Snøhvit project [56] and will be used in the Northern Lights project, which will come onstream in 2024 [57]. The more expensive "ship-to-platform" and "ship-to-subsea" concepts have not been attempted, and probably will only be used in special cases where transport using a subsea CO_2 pipeline is not feasible.

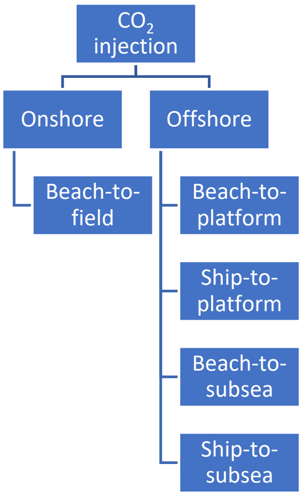


Figure 10. Development concepts for CO_2-injection.

6.1.6. Southern Lights: A Cross-Border CCS Project in ASEAN

In this roadmap, we propose a first-of-a-kind cross-broader CCS project in the ASEAN region called "Southern Lights." The naming of this project was inspired by the Northern Lights CCS project currently underway in Norway [58]. The Southern Lights project will capture CO_2 from Jurong Island in Singapore and transport it to a storage site in a nearby country, where it will be injected into a reservoir for permanent storage. In addition, this project can also accept CO_2 from the host country for storage (Figure 11). In future, CO_2 from other ASEAN countries can also be accepted. Phase 1 of the project will involve capturing, transporting, and storing 1 to 5 Mtpa CO_2 from Singapore and the host country. Phase 2 will involve ramping up storage to 10 Mtpa or higher [9,59].

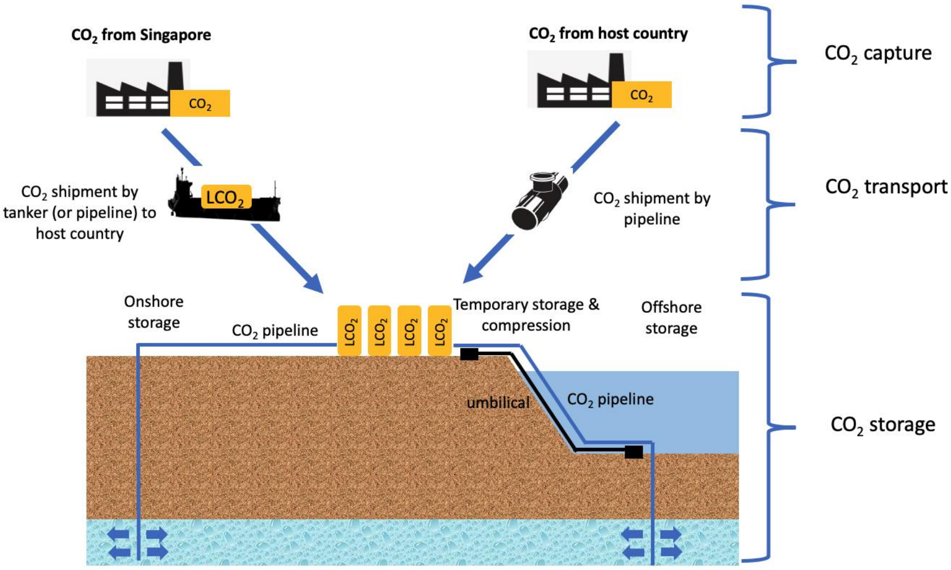


Figure 11. Southern Lights: a cross-border CCS project in the ASEAN region.

6.2. Hydrogen Production

The second initiative of the decarbonization roadmap is to build a steam methane reforming (SMR) plant in Jurong Island to produce hydrogen from natural gas and use CCS to remove the emitted CO_2 [59]. SMR is performed by mixing steam with natural gas to a high temperature in the presence of a catalyst. This process converts natural gas into hydrogen and CO_2. The hydrogen may be sold as a clean energy carrier for use in hydrogen fuel cell vehicles, as well as heating and as feedstock for industrial use. This process will allow Singapore to be a producer of hydrogen for domestic consumption and export. Already, countries such as Japan and South Korea are planning to import hydrogen from overseas and include it in the future energy mix [34,36]. In addition, Australia, New Zealand, Saudi Arabia, and the UAE have announced their desire to export hydrogen to Asia [37,60–62]. It is estimated that the global demand for industrial hydrogen will increase from 87 million tons in 2020 to 212 million tons in 2030 and 528 million tons in 2050 [63]. There is much for Singapore to benefit from if it can become a regional hub for exporting hydrogen. CCS will be a key technology enabling this to happen. New industries such as CCS and hydrogen may well become one of the new growth engines for the Singapore economy.

6.3. Transforming Refining

The refining sector is the biggest CO_2 emitter in Singapore, amounting to 43% of total emissions. Consequently, reducing Singapore's refining output and replacing it with low-carbon industries can make a difference in reducing Singapore's CO_2 emissions. Transforming Singapore's refining industry is therefore a key component of our roadmap to reduce overall CO_2 emissions.

Worldwide, many oil companies are reducing their refining capacity or shutting down refineries to reduce CO_2 emissions during the refining process. Shell has recently announced it is cutting the capacity of its Bukom refinery from 500,000 bbl/d to 300,000 bbl/d by July 2021 [64,65]. On the other hand, ExxonMobil has plans to expand the capacity of its largest refinery in Jurong Island from 592,000 bbl/d by another 48,000 bbl/d [66,67]. The overall reduction in refinery capacity in Singapore will reduce CO_2 emissions in this sector.

In addition, demand for conventional transportation fuels is forecasted to drop due to the desire to reduce CO_2 emissions in this sector [68]. At the same time, the demand for low-carbon fuels such as biodiesel, bioethanol, and renewable aviation fuels will increase at the expense of conventional fuels. This trend will accelerate in the future. A concomitant trend is the increase in demand in Asia for petrochemicals. As the population in Asia increases and countries become more prosperous, the demand for petrochemical products such as plastics, fertilizers, packaging, clothing, digital devices, medical equipment, detergents, and tires will increase. Plastics are also found in solar panels, wind turbine blades, batteries, thermal insulation for buildings, and electric vehicle parts. Petrochemicals will become the biggest driver of global oil demand, surpassing transportation fuels [69].

To survive the energy transition, the refining sector needs to become less carbon-intensive. Figure 12 shows the connection between the refining and petrochemical industries in Singapore. There are several ways to transform the refining industry (Figure 6). One is for refineries to reduce the output of conventional fuels. The second is to increase the output of feedstock to the petrochemical industry as demand for petrochemicals is expected to increase. A third way is to convert some crude refining capacity into biorefineries. Instead of refining crude oil, refineries may be converted to refine biomass to produce biofuels and bio-naphtha to be used by the petrochemical industry. A fourth way is to use post-combustion carbon capture to reduce CO_2 emissions from refineries. Figure 13 shows the connection between the refining industry and other industries after the transformation.

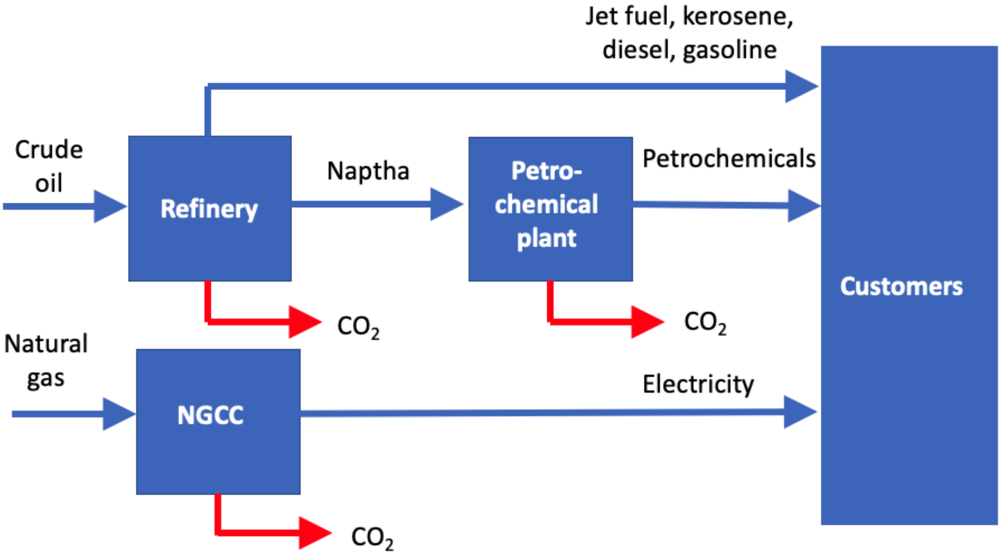


Figure 12. Current nexus between the power, refining, and petrochemical industries in Singapore.

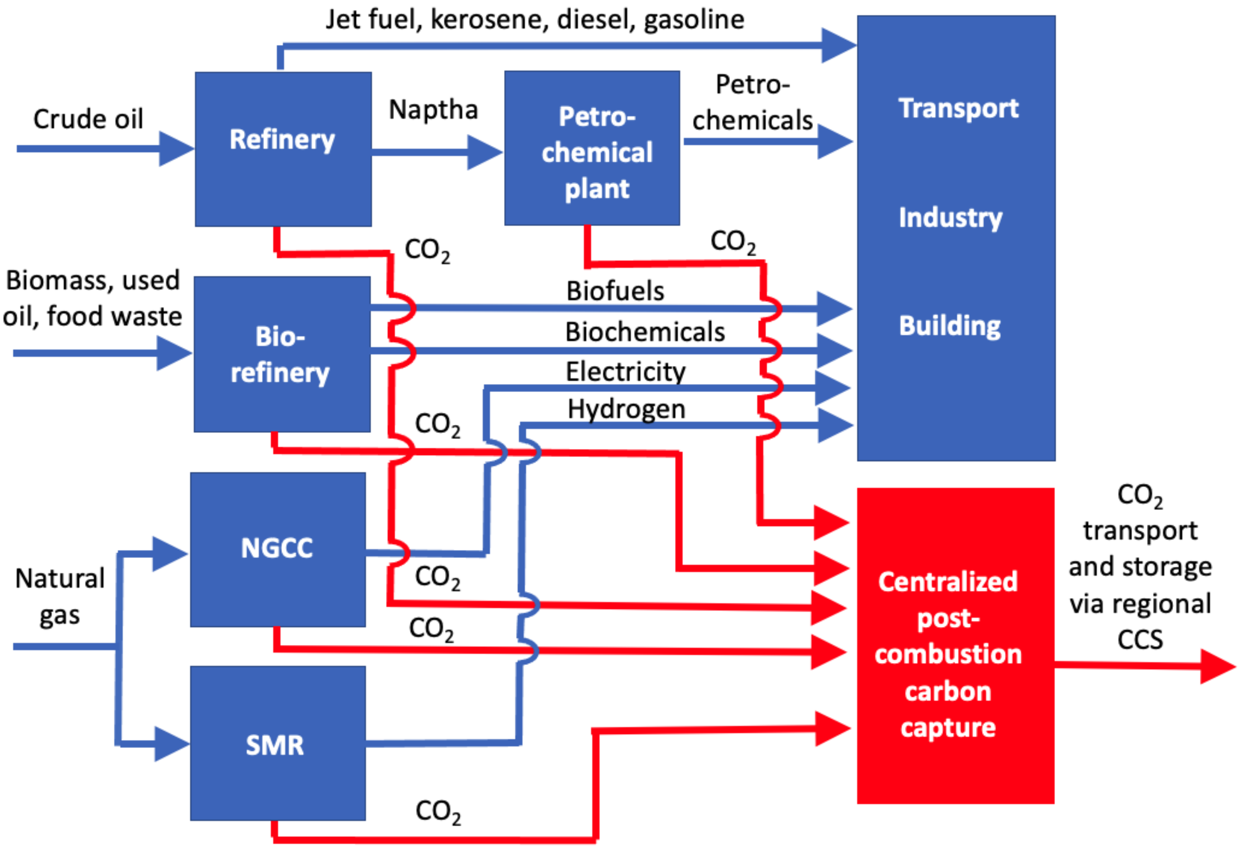


Figure 13. Future nexus between the power, refining, hydrogen, and petrochemical industries after transformation.

6.4. Refueling Transport

In the road transport sector, the chief CO_2 mitigation method is to replace internal combustion engine (ICE) passenger cars by electric vehicles (EVs) and long-haul ICE vehicles by hydrogen fuel cell vehicles (HFCVs). Already, Singapore has announced plans to phase out all internal combustion vehicles by 2040 [70]. For the marine transport sector, fossil-fuel based fuels are expected to be replaced by hydrogen. For the aviation transport sector, current jet fuels are expected to be replaced by biofuels. Singapore already has one of the biggest biofuel refineries in the world, with a capacity of 1.3 Mtpa [71]. However, jet fuel produced from the biorefinery is sold to North America and Europe, instead of being used in Singapore. The complete replacement of ICE vehicles by EVs and HFCVs will eliminate almost 7 Mtpa of mobile CO_2 emissions, which will be replaced by stationary CO_2 emissions during the processes of power and hydrogen generation. Again, CCS may be needed to remove CO_2 emitted from these stationary sources.

7. Energy Policy Implications

There are many important implications on Singapore's energy policies that can be derived from the roadmap. In this section, we will discuss only the major implications.

7.1. Energy Policy

A consistent long-term energy policy will provide incentives for individuals and companies to reduce CO_2 emissions, such as the adoption of a circular economy, tax credits for electric vehicles, and the installation of solar panels. Without this, individuals and companies may be hesitant to implement low-carbon-intensity technologies which will increase the overall cost of living or doing business. National targets may include the deployment of renewable energies and the imposition of a carbon tax or credits, among other strategies. Within ASEAN, countries that have set targets for renewable energies include Malaysia (35% by 2050), Indonesia (15% by 2025), Thailand (20% by 2022), and Vietnam (5% by 2020). Although Singapore has set targets to reduce CO_2 emissions over time, it has yet to set targets on how to achieve it, e.g., by increasing the percentage of renewable energies such as solar PV and biofuels, CCS goals, raising carbon taxes, or levels of hydrogen usage. Such national goals will be useful for incentivizing and guiding the overall energy transition pathway. The following are some components of such a national energy policy.

7.1.1. Carbon Tax

Since 2019, the Singapore government has imposed an SGD 5/tCO_2e tax on any company that emits more than 2000 tCO_2e per year of GHG. Singapore is the first ASEAN country that has imposed a carbon tax and there are plans to review this tax in 2023 and increase it to SDG 10–15/tCO_2e by 2030. Even at SGD 15/tCO2e ($11/$tCO_2e$), Singapore’s carbon tax is a far cry from the $50–120/$tCO_2e$ carbon tax in some European nations or the $35–50/$tCO_2e$ 45Q carbon tax credit in the US. To fund its decarbonization efforts, the Singaporean government may consider raising the carbon tax to a level on par with the US. There is a counterargument that a higher carbon tax may drive the refining and petrochemical companies away from Singapore. However, as mentioned earlier, an overall reduction in the refining capacity in Singapore is already happening, regardless of any change in carbon tax.

7.1.2. Target for Renewable Fuels

Besides setting targets for solar PVs and importing electricity from the regional grid, the Singaporean government can set targets on the use of renewable fuels in land, marine, and aviation transport. This will incentivize the modernization of Singapore’s refining industry to produce low-carbon transportation fuels such as biodiesel, bioethanol, and aviation biofuels. Biofuels can be blended with fossil fuels for use in transport. Singapore’s Changi Airport is one of the world’s major aviation hubs. Making aviation biofuels available in Changi Airport will be a major step toward reducing CO_2 emissions in the aviation industry.

7.1.3. A Hydrogen Roadmap

Establishing a national roadmap for hydrogen will be useful and important for determining the direction of Singapore’s energy transition. It will also accelerate private sector investment in hydrogen infrastructure, production, and transport. Singapore stands to gain if it becomes the center for hydrogen production in Southeast Asia [9,59]. This is especially true if cheaper natural gas imported by pipelines from nearby countries, rather than expensive LNG imported from distant countries, can be used for hydrogen production in SMR. In addition, with Singapore’s experience in petrochemicals, a SMR plant with higher capacity may be possible in Singapore compared to other countries. Already within Asia, countries including Japan, South Korea, New Zealand, and Australia have published their national hydrogen roadmaps which outline the direction of their hydrogen industries [34,36,37,60]. Singapore is the top bunkering port for the global marine industry, attracting 130,000 vessel calls annually [72]. Making hydrogen available as a bunkering fuel in Singapore will be a major step toward decarbonizing the marine and shipping industry.

7.1.4. Public Engagement on CCS

At present, public awareness and acceptance of CCS is low within ASEAN countries. There are those who oppose CCS because they think it is a way to prolong the use of fossil fuels. Public engagement on the sustainability and benefits of CCS by trusted experts will be needed to raise the level of awareness and increase public acceptance. Trusted experts should include those from government, technology providers, and institutes of higher learning [53]. It is important that the economic benefits of CCS in providing new CCS supply chains and employment opportunities be articulated during public engagements.

7.1.5. ASEAN Engagement on a Regional CCS Corridor

As Singapore does not have subsurface reservoirs for permanent CO_2 storage, the establishment of a regional CCS corridor will be important for the success of Singapore's decarbonization effort. Intergovernmental engagement between Singapore and its neighbors will be needed. The terms of a long-term CO_2 injection contract between countries may have many similarities with those of production sharing contracts (PSC) commonly used between host governments and oil and gas companies. It is not uncommon for PSCs to last for two decades or longer, specifying terms for both the host government and the oil company. Establishing one or more open-access ASEAN CCS corridors will be a major step toward decarbonization of the region. Since it is ASEAN's purpose to facilitate economic cooperation between member states, government-to-government engagement to implement an open access cross-border CCS project may be carried outs under the sponsorship of ASEAN.

7.1.6. CCS Regulations

The movement of CO_2 across borders is regulated by the London Protocol and the Basel Convention [73,74]. However, apart from the Philippines, ASEAN countries are not signatories to the London Protocol. Consequently, new international laws need to be promulgated within ASEAN to govern the movement of CO_2 across borders. In addition, national regulations on CO_2 injection and monitoring will be needed. Furthermore, the transfer of long-term liability from the operator to the government will be needed to de-risk a CCS project and obtain financing. Indeed, political leadership is needed if a cross-border CCS project is to be implemented.

7.1.7. Public-Private Partnership

The implementation of a CCS project requires an organization to plan, execute, and operate the project. Furthermore, this project will likely involve companies from multiple countries. The formation of a public–private partnership (PPP) partially supported by the Singaporean government will be beneficial for implementing the project. Professionals with relevant expertise and experience may be seconded from various organizations to the PPP.

7.1.8. Funding CCS Research and Development

The lack of CCS expertise in ASEAN countries needs to be addressed. At present, CCS expertise lies mostly in Europe and the US. International cooperation in research and development, as well as project execution in CCS should be encouraged to facilitate the transfer of expertise from Europe and the US to local entities. In addition, research and development on technologies relevant for the CCS project should be encouraged by ASEAN governments through research and technology funding.

8. Conclusions and Policy Implications

Based on an analysis of Singapore's energy landscape and the results of a technology mapping exercise, we propose a roadmap for the country to achieve net-zero emissions before 2100. This roadmap consists of four components. The first and most important component is capturing CO_2 from multiple sources in a centralized post-combustion carbon capture plant in Jurong Island. The captured CO_2 is then transported by ship or a pipeline to a neighboring country to be stored permanently in a subsurface reservoir. Essential to the success of this first-of-a-kind cross-border CCS project is the establishment of a regional CCS corridor which makes use of economies of scale to reduce the cost of CO_2 capture, transport, and storage. The second component is the production of hydrogen from natural gas using an SMR plant and integrating this plant with the centralized carbon capture plant. The third component is modernizing the refining sector to include, among other factors, biorefineries to produce renewable biofuels and biochemicals. The fourth component is refueling the transport sector by replacing ICE vehicles by electric and hydrogen fuel cell vehicles, while using biofuels for aviation and hydrogen for ships. The policy implications of this roadmap include imposing an adequate carbon tax, setting targets for renewable fuels, setting a roadmap of energy transition which includes the use of hydrogen, engaging the public to raise the awareness and acceptance of CCS, inter-governmental engagement to establish an ASEAN CCS corridor, the promulgation of CCS regulations, the setting up of a PPP for CCS project implementation, and providing funding for regional CCS research.

Author Contributions: Conceptualization, H.C.L. and S.R.; investigation, K.Z. and M.Z.S.H. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Petroleum Engineering Professorships Programme Grant (S13-1392-RF-Petroleum) awarded by the Economic Development Board of Singapore.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

Nomenclature

ASEAN	Association of Southeast Asian Nations. They include Indonesia, Malaysia, Thailand, Philippines, Vietnam, Laos, Myanmar, Cambodia, Singapore, and Brunei Darussalam.
bbl/d	Barrels per day
CCS	Carbon capture and storage
CCU	Carbon capture and utilization
CO_2	Carbon dioxide
CO_2e	Carbon dioxide equivalent
DEA	Diethanolamine
EV	Electric vehicle
GHG	Greenhouse gas
Gt	Giga ton, 10^9 tons
HFCV	Hydrogen fuel cell vehicle
H_2	Hydrogen
ICE	Internal combustion engine
MDEA	Methyl diethanolamine
MEA	Monoethanolamine
MMbbl	Million barrels
MMP	Minimum miscibility pressure of CO_2 with oil
Mtpa	Million tons per year
NaOH	Sodium hydroxide
NGCC	Natural gas combined cycle
OGIP	Original-gas-in-place
OOIP	Original-oil-in-place
PPP	Public private partnership
PSC	Production sharing contract
SMR	Steam methane reforming
Solar PV	Solar photovoltaic
$	US dollar
SGD	Singaporean dollar
Tcf	Trillion standard cubic feet, 10^{12} ft^3

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