Chapter 1

Geological Storage Potential of CO_2 in Southeast Asia

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1.1. Southeast Asian CO_2 Storage Resource Development

Storage assessments in Southeast Asia have been limited, with most assessments focusing only on oil and gas fields and lacking supporting data. The last regional study of Southeast Asia was the Asia Development Bank's (ADB) *'Prospects for CCS In Southeast Asia'* report from 2013 (ADB, 2013). The techno-economic report was comprehensive but only focused on four countries: Viet Nam, Thailand, Metro Manila (Philippines), and South Sumatra in Indonesia. The report detailed a roadmap for deployment, focusing initially on pilot plants that could be upscaled to commercial facilities, finding natural gas processing and power plants had the best chances of successful commercialisation.

The ADB (2013) report found that the storage resource estimate for the four nations was 54 $GtCO_2$, with the vast majority (88%) of resources held in saline formations. Hydrocarbon fields were also assessed, with only 3.5 $GtCO_2$ storage resources across 143 fields. Unfortunately, the saline formations, fields, or the data behind the methodology and calculation were not provided, meaning no further progress could be made. Since the 2013 ADB study, no regional studies have characterised saline formations, hydrocarbon fields or completed source-sink matching exercises. These types of analysis are critical for ongoing storage resource development.

This current analysis aims to identify strategic storage resources in saline formations and hydrocarbon fields adjacent to clusters of industries where CCS can be applied. These emission-intensive clusters include power generation, chemical, cement and steel production, gas processing, and oil refining. A process known as source (industrial emissions sources)-sink (storage resources) matching. Source-sink matching identifies early mover opportunities for CCS development.

1.1.1. Current CCS Deployment Status

Despite Southeast Asia being a focus for CCS for over a decade, CCS facility deployment is very low compared to other parts of the world. indicates the current CCS facilities at various stages of development in the region. There are no operational facilities, with Petronas currently building the Kasawari CCS facility in the Sarawak Basin, Malaysia. Petronas and PTTEP also plan a second facility, Lang Lebah, in the same basin. That project is currently suspended, citing an unclear regulatory framework. Petronas and J.X. Nippon are planning the BIGST Project, a joint plan to explore opportunities for gas potential and CCS in the Bujang, Inas, Guling, Sepat, and Tujoh (BIGST) fields, situated offshore in Kerteh, Terengganu.

Indonesia hosts eight vertically integrated CCS facilities from various industries, but all are led by the oil and gas sector, focusing on gas processing, hydrogen/ammonia production and oil refining (Table 1.1). The Arun CCS Hub in Aceh is planned to be a multi-user storage site. In addition, the pilot Gundih Project plans to start injecting in 2024.

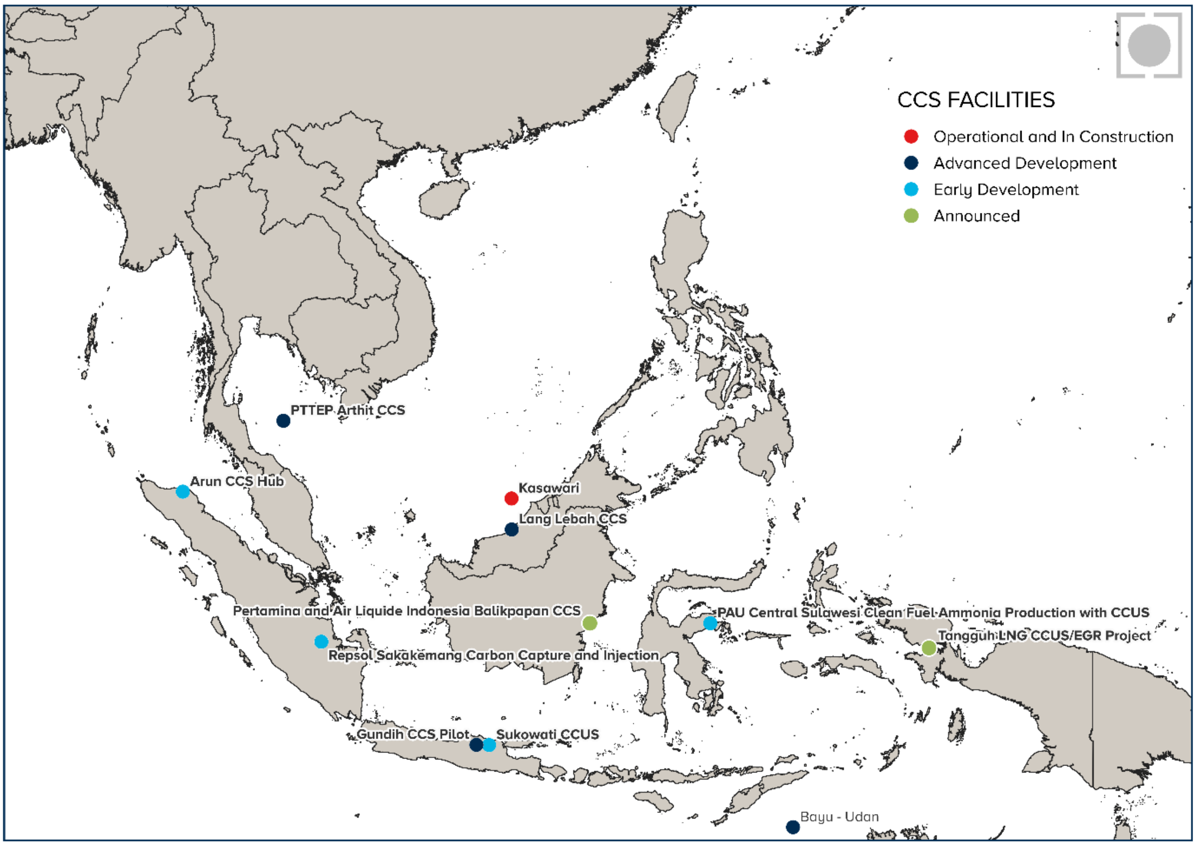
In Thailand, PTTEP is planning the Arthit facility in the Pattani Basin offshore Thailand (Figure 1.1).

Table 1.1. Commercial CCS Facilities in Indonesia

Commercial Facility	Status	Planned Operational Date	Industry
BP Tangguh LNG	Advanced Development	2026	Natural Gas Processing
Carbone Aceh Arun Hub	Early Development	2029	CO_2 Transport / Storage
ExxonMobil Indonesia Regional Storage Hub	Early Development	Under Evaluation	CO_2 Transport / Storage
PAU Central Sulawesi Clean Fuel Ammonia	Early Development	2025	Hydrogen / Ammonia / Fertiliser
Pertamina and Air Liquide Indonesia Balikpapan	Announced	Under Evaluation	Hydrogen / Ammonia / Fertiliser
Pertamina Jatibarang	Advanced Development	Under Evaluation	Natural Gas Processing
Pertamina Sukowati	Early Development	2028	Oil Refining
Repsol Sakakemang	Advanced Development	2026	Natural Gas Processing

Source: GCCSI.

Figure 1.1. CCS Facilities in Southeast Asia



Note: the locations of Jatibarang and the ExxonMobil Regional Storage Hub were unknown at the time of map production.
Source: CO2RE, 2023

1.2. Methodology

The methodology for completing source-sink matching requires two steps. First, a basin suitability assessment is conducted to identify potential basins for CO2 storage. Potential basins near industrial emission clusters are then prioritised. Second, the CO2 storage resources in hydrocarbon fields and saline formations are estimated within those storage basins and the CO2 EOR-storage potential is calculated.

The analysis incorporates only selected Southeast Asian nations with suitable storage and data. Importantly, not all emission clusters and storage basins were detailed across Southeast Asia, which means that the CCS networks presented below should be viewed as a preliminary guide for future studies.

1.2.1. Basin Suitability Assessment and Source Sink Matching

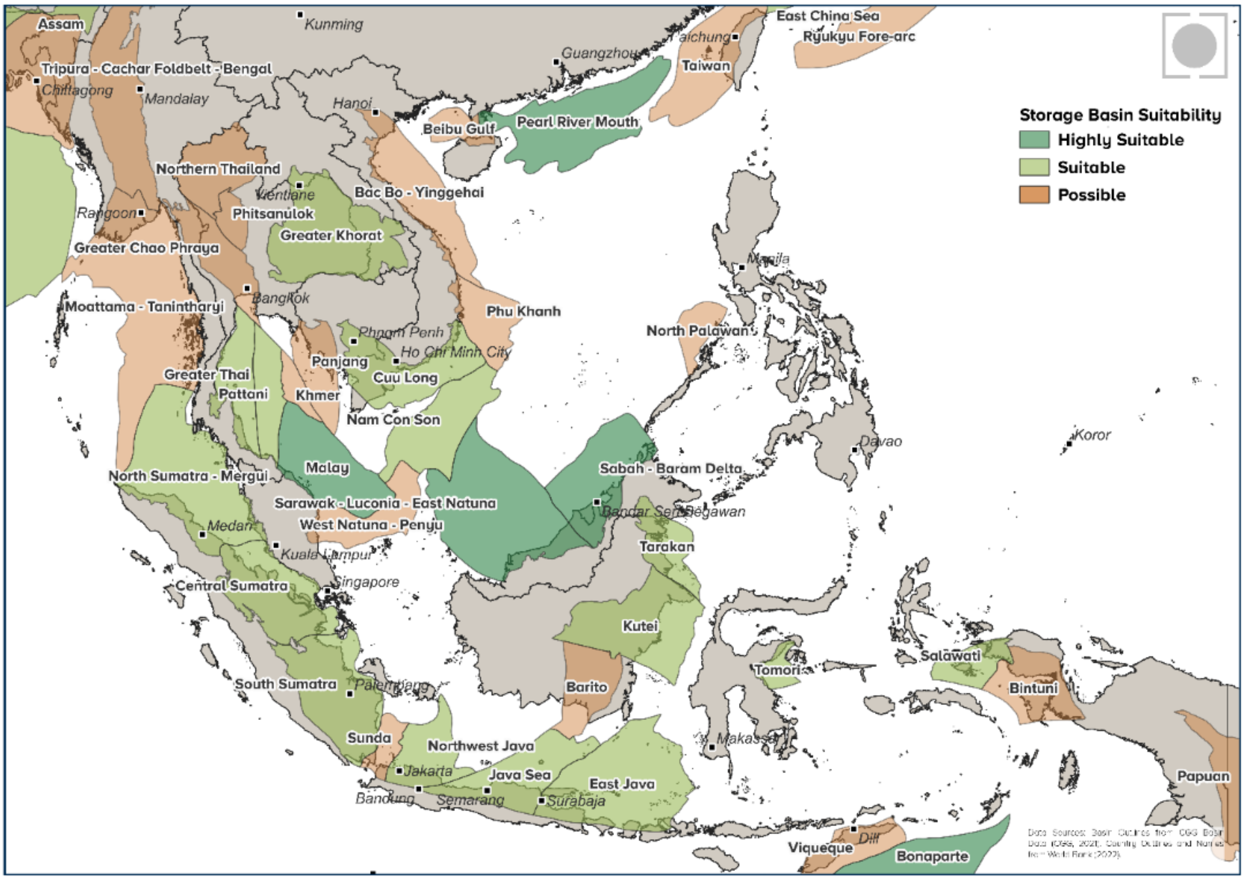
The following steps were completed to identify focus areas for CO_2 storage development in Southeast Asia proximate to CO_2 source clusters:

1. The Institute's storage basin assessment tool was used to assess every Southeast Asian basin (Figure 1.2); more information on the assessment methodology can be

found in Appendix A. The outcome of the basin assessment tool was to categorise each basin as either:

- ✓ Highly suitable (dark green in maps). These basins have most, if not all, the following characteristics:
  - Optimal geology for storage
  - Completed multiple detailed assessments of its storage characterisation and resource estimates by multiple parties with consensus on results
  - In most instances, the injectivity and storage of CO_2 have been tested, undertaken (pilot/EOR) or modelled.
  - The basin hosts a commercial-scale storage operation or advanced planning
  - The basin is (or has been) a mature and major oil and gas producer
  - The basin is accessible to CO_2 storage operations
- ✓ Suitable (light green). These basins meet many properties of a highly suitable basin, but generally:
  - Optimal geology for storage
  - Storage assessments have been more localised on particular parts of the basin
  - Do not host active or completed storage operations (commercial or pilot)
  - CO_2 storage operations may have accessibility issues
- ✓ Possible (orange). These basins have the following:
  - Prominent indicators of viable storage geology, such as oil and gas operations suggesting viable reservoirs and seals for CO_2
  - Storage analysis is limited to only broad, regional assessments, generally focusing on the oil and gas fields
  - Can have significant accessibility issues for CO_2 storage operations
- ✓ Unlikely (red). These basins generally have either:
  - Obstructing accessibility issues for CO_2 storage operations
  - The geology is currently defined as unsuitable for CO_2 storage. For example, a shallow (<800 m) basin means that CO_2 would not be stored in a supercritical phase, decreasing storage efficiency and increasing plume movement.

Figure 1.2. Southeast Asia Basin Suitability Assessment



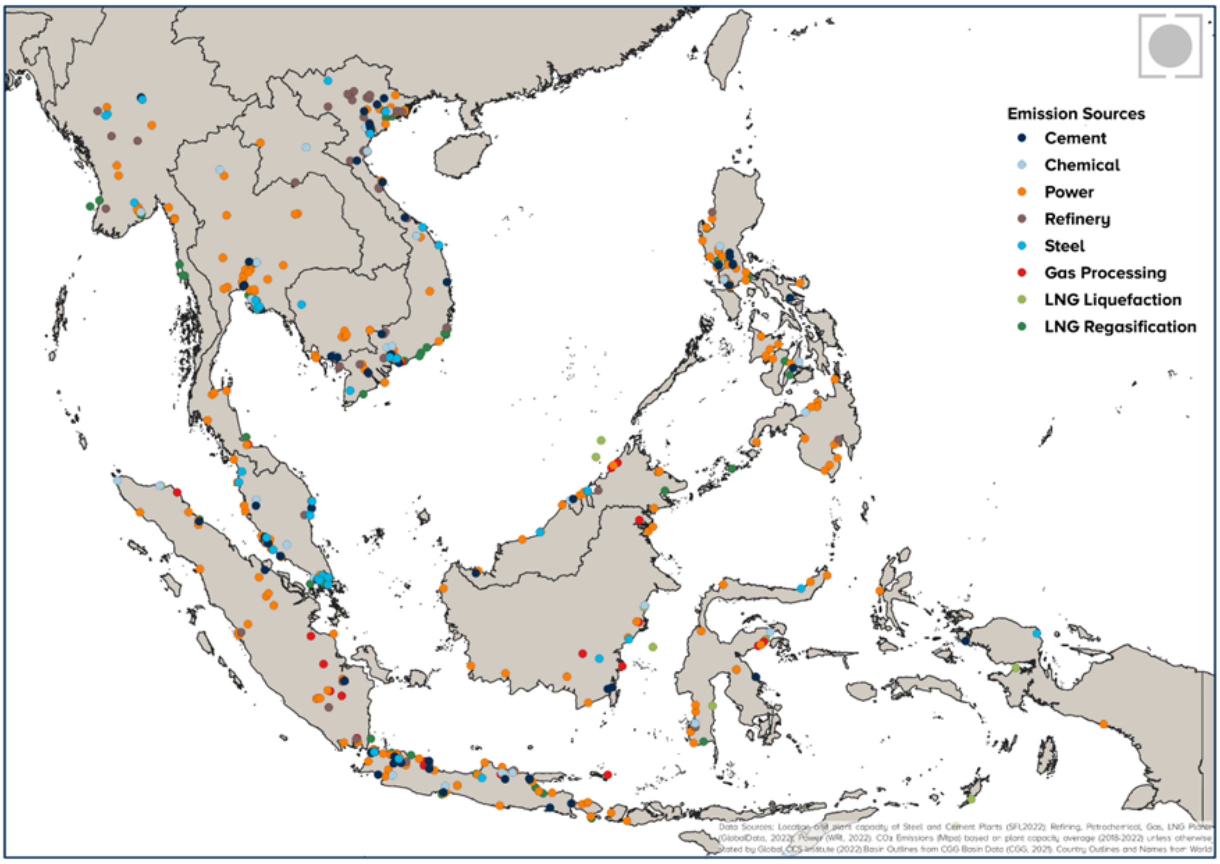
Note: This figure does not show basins categorised as 'Unlikely'.
Source: GCCSI.

2. The second step was to identify industrial emission clusters.
   - ✓ All industrial plants where CCS could be applied were identified in the region (Figure 1.3). The sector, the number of plants and sources of data are presented in Table 1.2.
   - ✓ The assumption for these plants is that each plant is operational and that the CO_2 emitted from the plants could be captured and transported for storage.
3. Grouping plants within 100 km of each other that could theoretically form clusters of emissions for a CCS network were identified. A distance of 100 km is arbitrary. However, techno-economic studies have found that pipelines greater than 100 km between capture plants or capture and storage sites become uneconomic because they require booster stations for compression.
   - ✓ The clusters are presented in the individual country maps (Figure 1.5; Figure 1.8; Figure 1.12; Figure 1.15; Figure 1.18).
4. Emission clusters were matched to their nearest storage basin.

   Note: A matching exercise comparing the cumulative emission rates of each cluster with their matching maximum cumulative injection rates and corresponding cumulative storage resources was outside the scope of this analysis.

5. Resource calculations for each suitable basin near an emissions cluster were the final step in this analysis. The resource calculation methodology is detailed in Section 1.2.2.

Figure 1.3. Emission Sources: Industrial Plants with the Potential to Host a Capture Unit Across Southeast Asia



Source: GCCSI

Table 1.2. Emissions Sources: Industrial Plant Data

Sector	Count of Plants	Source of Data
Power Generation	331	Byers, 2022
Cement	76	McCarten, 2022
Chemical	46	GlobalData, 2022
Refining	91	GlobalData, 2022
Steel	41	(Global Energy Monitor, 2022)
Gas Processing	41	GlobalData, 2022
LNG Liquefaction and Regasification	90	GlobalData, 2022

Source: GCCSI

1.2.2. Resource Calculation

1.2.2.1. Depleting and Depleted Hydrocarbon Fields

This analysis considered depleting and depleted fields. In a depleted hydrocarbon field, the majority of the economically recoverable oil or gas has already been extracted, leaving behind a relatively small amount of hydrocarbons that are uneconomical to produce using conventional drilling and extraction methods. Depleted fields may still contain some residual hydrocarbons, but the cost of extracting them may outweigh the potential profits. Depleting fields means the field is in production and still has economically recoverable oil or gas. This study did not have any metrics to distinguish between depleted and depleting fields, as the ultimate aim was to estimate available, remaining, and net CO_2 storage resources.

CO_2 storage resource estimates for depleting and depleted conventional oil and gas fields were calculated using the approach published by the United States Geological Survey (Brennan et al., 2010). This method assumes that some portion of the reservoir pore volume originally occupied by hydrocarbons produced from that reservoir can be replaced with injected CO_2. As such, the estimated CO_2 storage resources (MCO_2) of the hydrocarbon fields can be calculated using Equations 1-3:

Equation 1

$$M_{CO2\ avaibale} = (N_{o-produced} . B_o + N_{g-produced} . B_g) . E . \rho_{CO2} \quad (1)$$

Equation 2

$$M_{CO2\ remaining} = (N_{o-remaining} . B_o + N_{g-remaining} . B_g) . E . \rho_{CO2} \quad (2)$$

Equation 3

$$M_{CO2\ net} = M_{CO2\ avaibale} + M_{CO2\ remaining} \quad (3)$$

Where:

- E refers to storage efficiency, which is ''site-specific'' and can be determined via reservoir simulations. The commonly used value for E in oil and gas fields is between 0.2 to 0.4.
- B_o and B_g stand for the formation volume factors of the oil and gas, respectively, dependent on oil and gas properties and current reservoir conditions.
- ρ_{CO2} represents the CO_2 density at reservoir conditions, a function of reservoir pressure and temperature.
- $N_{o-produced}$ and $N_{g-produced}$ refers to the produced volume of the oil and gas in a field.
- $N_{o-remaining}$ and $N_{g-remaining}$ refers to the remaining volume of oil and gas in a field.
- $M_{CO2\,avaibale}$ refers to the storage resources currently available due to hydrocarbons that have been produced.
- $M_{CO2\,remaining}$ refers to remaining storage resources in a field that can become available upon production of the hydrocarbons (the field becomes depleted).
- $M_{CO2\,net}$ refers to the net CO_2 storage resources of a field.

Hydrocarbon Fields: Assumptions and Limitations

Recovered resource volumes for hydrocarbon fields were obtained from the hydrocarbon reserves database compiled by Global Data. In many instances, essential field data, such as average depth, temperature, and pressure, were unavailable. To address the missing data issue, the depth was estimated using a well's True Vertical Depth (TVD) within the field, or an arbitrary depth of 1200 m was assumed.

The acquired depth data were then employed to calculate the average field pressures, utilising a hydrostatic pressure gradient of 1.45 psi/m.

The depth data was also used to determine the average field temperatures using a Gaussian probability distribution (Monte Carlo) defining the geothermal gradient's minimum, maximum, and standard deviation values, as presented in Table 1.3.

Utilising the calculated pressure and temperature data, densities of CO_2 and CH_4 were calculated for each field. Assuming that natural gas within each field, if present, is completely made of CH_4 and utilising the CH_4 specific gravity of 0.554, the gas formation volume factor (B_g) for each field was computed.

Regarding the oil formation volume factor (B_o), due to data limitations, minimum, maximum, and standard deviation values reported in Table 1.3 were defined. These values were used to calculate the oil formation volume factor for each field using a Gaussian probability distribution. Table 1.3 also presents the values used in calculating storage efficiency for each field using the Gaussian probability distribution. A Monte Carlo simulation was employed to estimate resources, conducting one thousand simulations with a sample size of five for each parameter in every simulation.

This study only examined producing and abandoned conventional oil and gas fields. Currently discovered or planned-to-be-produced fields were not assessed due to data limitations. More importantly, these fields would not be ready for CO_2 storage until they become depleted, or in the case of oil fields, until their primary production recovery rate becomes so low that it justifies CO_2 EOR storage. Furthermore, the fields were screened based on their depth and P50-net CO_2 storage resources, and only fields with a depth equal to or higher than 800 m and net storage resources greater than 5 $MtCO_2$ are reported here. The depth criterion is crucial because CO_2 would not be in a supercritical phase in shallow fields. The 5 $MtCO_2$ screening criterion is applied because fields with smaller volumes would not offer economically viable CCS project opportunities.

It should be noted that the calculated average pore pressure, temperature, gas formation volume factor, and estimated oil formation volume factor values for each field obtained through the above methodology may not precisely represent the actual values in each field. However, the utilised methodology is the most reliable approach to understanding the storage resources of the fields. A detailed analysis of each field is essential to acquire accurate information regarding its storage resources.

Additionally, water and gas production during primary production, as well as water flooding or any other secondary injection techniques that may have been applied to some fields, are beyond the scope of this study. The equations used account only for the physical trapping of CO_2 and do not consider solubility trapping.

Understanding the local geological conditions is out of the scope of this analysis. Hydrocarbon fields are assumed to have a viable reservoir(s) and overlying seal(s). Furthermore, the calculation does not consider pore-space connectivity and assumes all pore spaces are available to CO_2. Compartmentalisation can negatively impact CO_2 storage resources.

Table 1.3. Parameters Used in the Monte Carlo Simulation to Estimate Storage Resources per Field

	Average	Min	Max	Standard Deviation
Geothermal gradient (°C/km)	33	23	40	6
B_o	1.5	1.1	2	0.2
E	0.3	0.2	0.4	0.04

Source: GCCSI

1.2.2.2. Saline Formations

Saline formations are deep (>800 m) geological bodies saturated with brine with a high total dissolved solids (TDS) concentration. According to underground drinking water sources (USDW) in the United States, those formations with TDS exceeding 10,000 mg/L can be targeted for CO_2 storage (US EPA, 40 CFR § 144.3, 2010). Since TSD data for formations were unavailable for this report, it is assumed the formations assessed herein could be potential targets for CO_2 storage.

The United States Department of Energy, National Energy Technology Laboratory (US DOE NETL) has developed a CO_2 storage resource calculator called CO_2-SCREEN, intended to be used as a high-level screening tool to predict the storable mass of CO_2 in saline formations (Sanguinito et al., 2022). The Python-based tool utilises Monte Carlo simulations to perform probabilistic resource estimates for saline formations, shale zones, and residual oil zones (ROZ). It is available for download from the US DOE NETL Energy Data Exchange website (EDX) here: https://edx.netl.doe.gov/dataset/CO2-screen (Sanguinito et al., 2022).

Version 4.1 of CO_2-SCREEN was used to estimate the CO_2 storage resource in the major saline formations in each highly suitable basin. The following data and assumptions were used when determining the physical parameters for the saline formations:

- Area – estimated from the distribution of well penetrations using the Global Data database
- Gross Thickness – averaged from well data in the Global Data database
- Porosity – averaged from well data in the Global Data database
- Pressure – estimated from the reservoir depth (using a hydrostatic gradient of 0.44 psi/ft when pressure data in wells was unavailable)
- Temperature – estimated from the reservoir depth (using a geothermal gradient of 33 °C/km when temperature data was unavailable)

Storage efficiency factors developed by the International Energy Agency Greenhouse Gas R&D Programme (IEA GHG, 2009) were used for resource estimation. Default IEA efficiency factors were selected for the relevant formation lithology and depositional environment (IEA GHG, 2009). Default net-to-total area, net-to-gross thickness, and effective-to-total porosity were also used.

Saline Formations: Assumptions and Limitations

Understanding the local geological conditions is out of the scope of this analysis. It is assumed there is a viable reservoir(s) and overlying seal(s) for saline formations. The analysis doesn't consider reservoir properties, such as porosity, permeability, pressure or temperature variations, or faulting. In addition, in the resource assessment, the calculation assumes that the pore space will be available for CO_2. The calculation does not consider pore-space connectivity. Saline formations could be heterogeneous or compartmentalised due to faulting, impacting storage resource estimates. This approach accounts only for the physical trapping of CO_2 and does not consider solubility trapping. Finally, the approach assumes that the saline formation has open boundaries, which may not be true for all formations. Therefore, the results may be overly optimistic.

1.2.2.3. CO_2 EOR-Storage (CCUS)

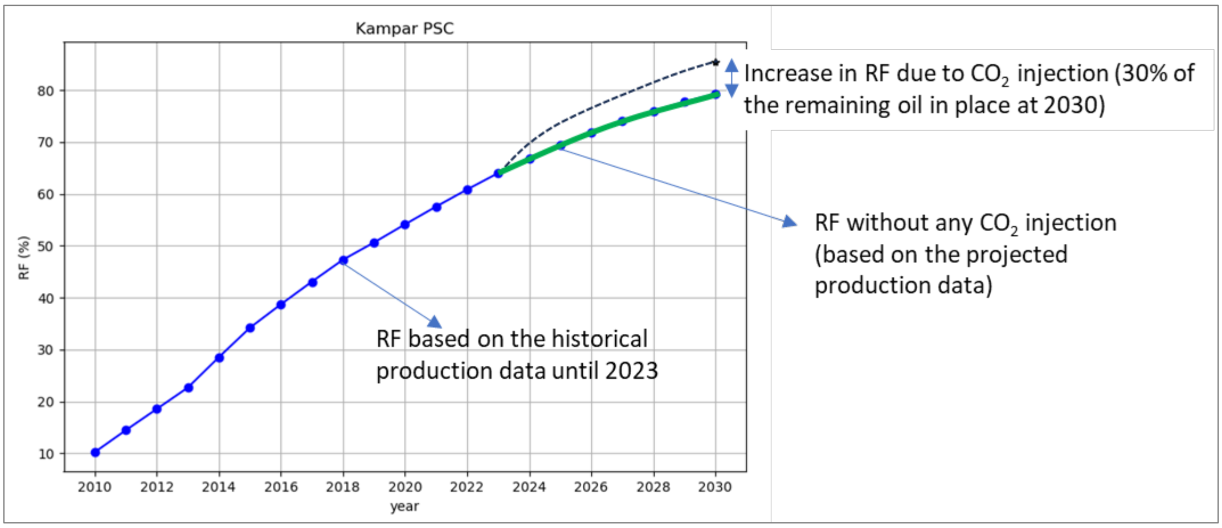
CO_2 EOR is a well-established oil and gas industry technique designed to enhance oil recovery. With a track record spanning over three decades of global operational experience, this technique has consistently demonstrated its effectiveness. The primary mechanisms driving oil recovery in CO_2 EOR are well-documented and extensively studied by many researchers. These mechanisms include oil swelling, oil viscosity reduction, and achieving miscible conditions when the reservoir pressure is higher than the minimum miscibility pressure (MMP).

The quantity of additional oil recovered through this technique depends on various parameters. These factors encompass the type of oil, the purity of the injected CO_2, the attainment of miscibility or near-miscible conditions, reservoir heterogeneities, the quantity and spatial distribution of residual oil in place, injection and production strategies and placement.

As such, a comprehensive analysis involving experimental and numerical studies for each field is essential to accurately determine a realistic recovery factor (RF), but this is beyond the scope of the present study. Therefore, a range of recovery factor values, spanning from as low as 5% to as high as 30% of the remaining oil in place, has been considered for this study.

By analysing oil production history data of oil fields from 2010 to 2023 and incorporating projected oil production rates until 2030 (sourced from GlobalData), each field's projected remaining oil in place by 2030 has been calculated. It is assumed that a reduction of 5%, 10%, 15%, 20%, 25%, or 30% in remaining oil in place by 2030 could be achieved through CO_2 EOR, thereby enabling the calculation of the additional oil that could be extracted by 2030 using CO_2 injection. For simplicity, only 5% and 30% results are reported here.

Figure 1.4. Recovery Factors (RF)



Note: the blue line indicates the primary recovery factor until 2023, the green line indicates the projected recovery factor from primary production until 2030, and the black dashed line shows the secondary recovery factor by CO_2 injection.
Source: GCCSI

During the CO_2 injection process, some injected CO_2 can become trapped within the reservoir through residual trapping, structural trapping, and solubility trapping. Solubility trapping encompasses the dissolution of CO_2 in the formation brine and within the residual oil. The solubility of CO_2 in oil depends on reservoir conditions and the specific type of oil. Nevertheless, this solubility can often be multiple times greater than the amount of CO_2 that can dissolve in the formation brine. Consequently, CO_2-EOR is also recognised as a CO_2 storage and utilisation technique (CCUS). The estimated CO_2 storage resources of the studied oil fields are calculated using equations 1 and 2 presented earlier.

CO_2 EOR-Storage: Assumptions and Limitations

It is assumed that oil field candidates for CO_2 EOR storage are those with a depth higher than 800 m, a storage resource exceeding 5 $MtCO_2$, a current recovery factor (RF) of less than 90%, and a projected primary remaining oil in place in 2030 greater than zero.

Note that, using equations 1-3, the consideration of the amount of CO_2 that can be stored through the displacement and production of water during CO_2 injection is omitted. High water cuts are expected during CO_2 EOR, and the pore space made available by such production provides additional CO_2 storage resources. Additionally, there is a high possibility of CO_2 breakthrough (i.e. injected CO_2 arriving at and being produced at production wells) and surface production during the injection. The breakthrough time varies depending on the injection, production strategy/design, and reservoir characteristics. It is assumed in this study that the produced CO_2 is separated and treated at the surface before being re-injected into the reservoir.

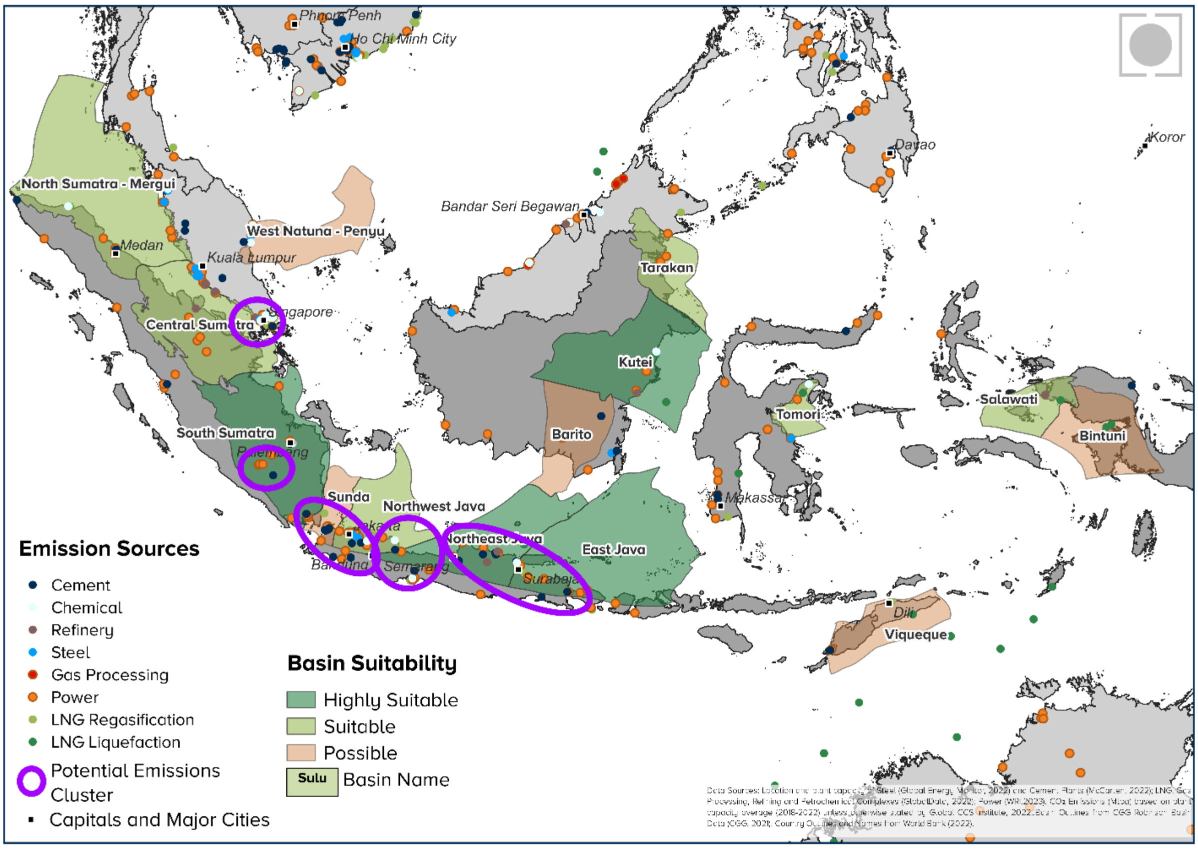
1.3. Results and Discussion

The outcomes of the source-sink matching exercise and the resource calculations are presented below. This analysis is supported by existing published literature where required.

1.3.1. Indonesia

Indonesia has a high overall CO_2 storage potential with abundant resources enabling a CCS Industry. Across Indonesia, four major emission clusters have been identified (Figure 1.5). There is the potential for numerous networks across Indonesia. In addition, the Singapore cluster is shown in Figure 1.5.

Figure 1.5. Indonesian and Singaporean Emission Clusters and Storage Basins



Source: GCCSI.

There is a major industry-led drive for CO_2 storage development in Indonesia, with support from international bodies (World Bank, 2015) to support CCS. Indonesia hosts the most CCS facilities in the region, with eight commercial facilities and one pilot (Gundih) distributed across the country (Figure 1.1). Six of the eight CCS facilities (PAU Central Sulawesi, Sakakemang, Tangguh LNG, Sukowati, Balikpapan, Jatibarang) are vertically integrated, with a capture plant having its own dedicated downstream transport and storage component. This reduces emissions from planned plants. None of these facilities has discussed broader access to their sites. However, the Arun CCS Hub in Aceh will be designed as a multi-user storage site. According to internal and external storage resource estimates, the depleted gas field has between 500 Mt - 1 GtCO_2 storage resources available (D. Lim pers. comm.).

1.3.1.1. CO_2 Storage Resources Summary

The estimated CO_2 storage resources of oil and gas fields (Table 1.4; Figure 1,6; Figure 1.7), CO_2-EOR Table 1.5, and saline formations (Table 1.6) are summarised below. Table1.6 shows the median (P50) cumulative net CO_2 storage resources ($\boldsymbol{M_{CO2\ net}}$) across studied conventional oil and gas fields per basin. As observed in the figure, the majority of storage resources are provided by gas fields, with the Kutei Basin having the highest net storage resources. The Kutei Basin also boasts the highest available storage resources (Table 1.4). Figure 1.6 displays the P50 net and available storage resources in the examined oil and gas fields. The figure reveals that many fields are relatively small, offering less than 20 MtCO2 net storage resources. This size constraint might render them unsuitable for average-sized, long-term commercial-scale CCS facilities, around 0.8 Mtpa over 20-40 years, according to capture rate data of the Global CCS Institute's CO2RE database (Global CCS Institute, 2023a). However, a more in-depth field assessment is necessary before making definitive conclusions.

Table 1.4. Indonesia: Estimated CO_2 Storage Resources in Hydrocarbon Fields

Basin	P50- Storage Available ($MtCO_2$)	P50- Storage Remaining ($MtCO_2$)	P50- Storage Net ($MtCO_2$)	Number of Gas Fields	Number of Oil Fields
Banggai-Sula Basin	23.4	25.3	48.7	2	0
East Java Basin	100.8	29.3	130.2	3	2
Kutei Basin	598.8	99.3	698.1	6	2
North East Java Basin	78.1	60.0	138.1	6	2
North Sumatra Basin	506.0	0.3	506.3	1	0
North West Java Basin	65.3	36.6	101.9	2	0
Sengkang Basin	5.3	0.0	5.3	1	0
South Sumatra Basin	281.9	143.7	425.6	6	3
Sunda Basin	44.3	1.8	46.1	0	1
Tarakan Basin	5.2	1.0	6.2	0	1
West Java Basin	4.2	2.1	6.3	0	1

Basin	P50- Storage Available ($MtCO_2$)	P50- Storage Remaining ($MtCO_2$)	P50- Storage Net ($MtCO_2$)	Number of Gas Fields	Number of Oil Fields
West Natuna Basin	137.8	24.4	162.3	2	1
Total	**1,851**	**424**	**2,275**	**29**	**13**

Note: Central Sumatra Basin is missing because all the studied fields are too shallow (<800 m depth).
Source: GCCSI

Table 1.5. Indonesia: Estimated CO_2 Storage Resources in Oil Fields Assessed for CO_2 EOR-Storage

Basin	P50- Storage Available	P50- Storage Remaining	P50- Storage Net	Extra Oil Recovery (MMbbl) @RF5%	Extra Oil Recovery (MMbbl) - @RF30%
East Java Basin	88.82	7.95	96.85	7.7	46.3
Kutei Basin	5.31	1.80	7.10	1.0	5.7
North East Java Basin	17.14	20.56	37.70	11.2	67.3
South Sumatra Basin	1.52	4.11	5.63	0.4	2.6
Tarakan Basin	5.23	0.98	6.21	0.6	3.8
Total	**118**	**35**	**153**	**21**	**126**

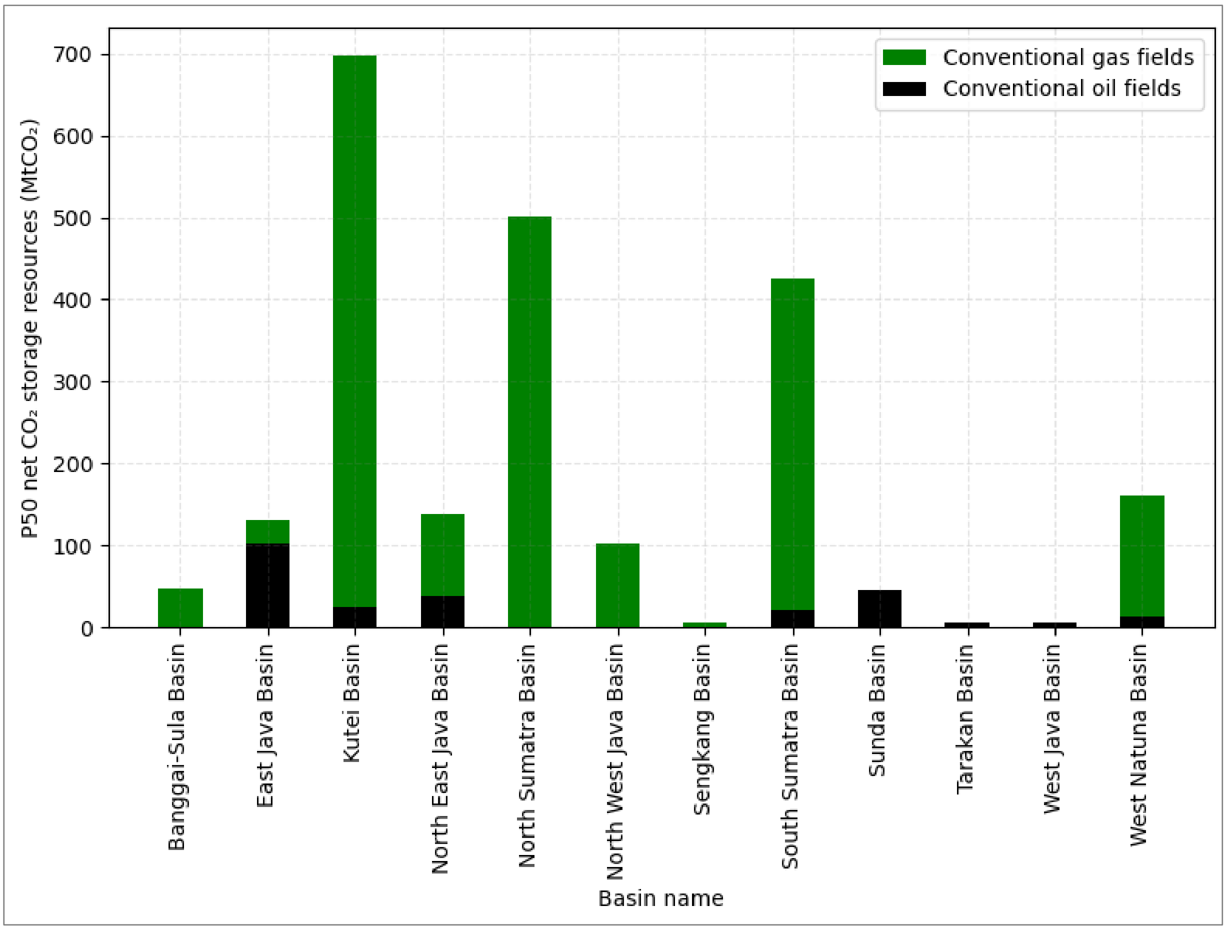
Source: GCCSI

Table 1.6. Indonesia: Estimated CO_2 Storage Resources in Saline Formations

Basin	Formation(s)	P10 ($GtCO_2$)	P50 ($GtCO_2$)	P90 ($GtCO_2$)
Kutei	Balikpapan Group	23	35	53
East Java	Kujung	4	8	13
Central Sumatra	Bekasap and Duri (Sihapas Group)	5	6	9
Total		**32**	**49**	**75**

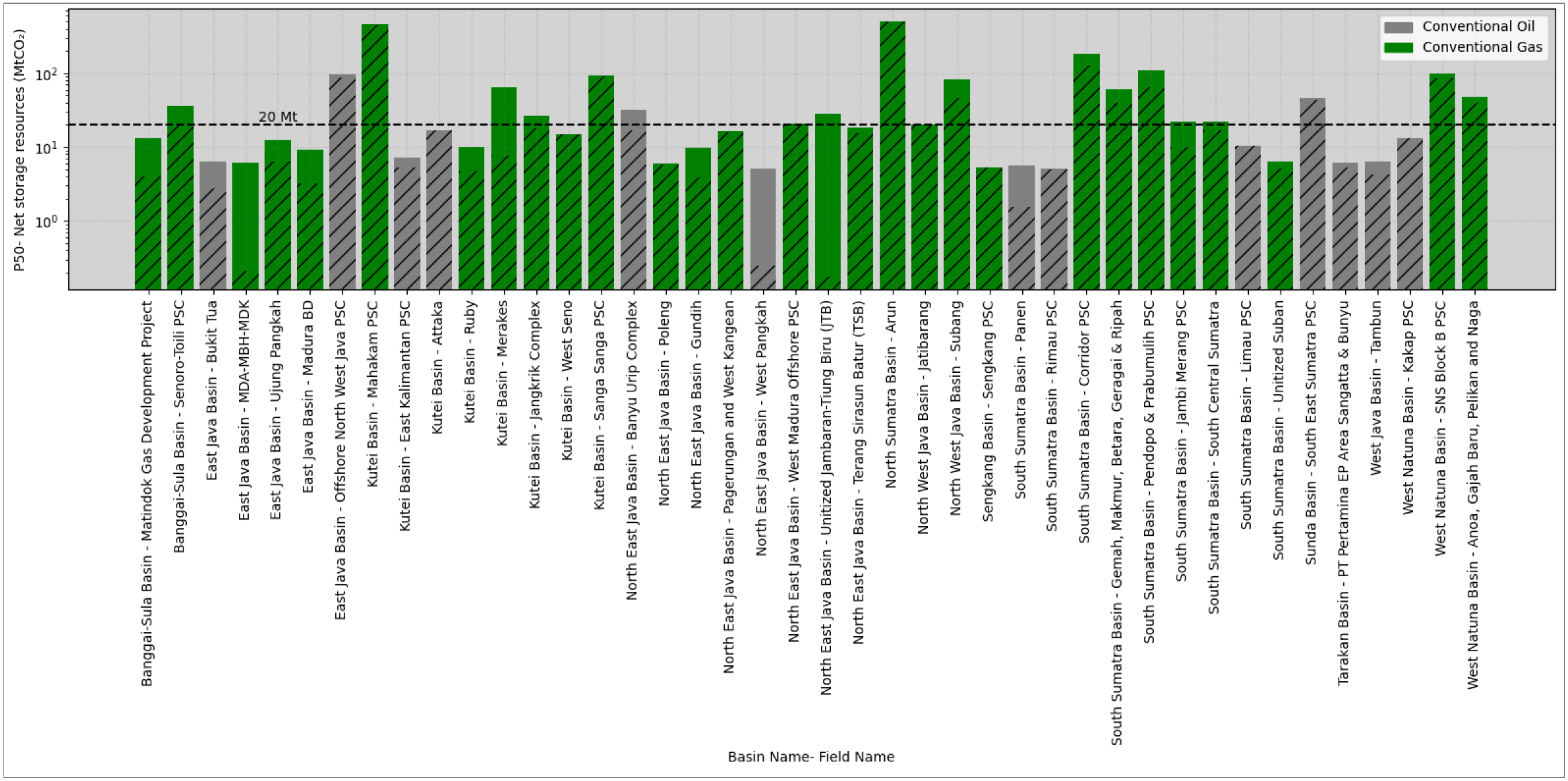
Source: GCCSI

Figure 1.6. Cumulative P50 CO_2 Storage Resources in Studied Oil and Gas Fields per Basin Across Indonesia



Source: GCCSI

Figure 1.7. P50- Net CO_2 Storage Resources of the Studied Oil and Gas Fields in the Indonesian Basins



Note: the available CO_2 storage resources are shown as a texture on the bars.
Source: GCCSI

1.3.1.2. Prospective Basins with Potential Clusters

According to the basin suitability analysis, Indonesia hosts 10 suitable basins (Figure 1.5) distributed across most of the islands of Indonesia. Unique to Indonesia, many of these basins extend from onshore to offshore. All these basins are oil and gas producers with proven reservoir-seal pairs and data availability. However, the subsurface data (such as well log and seismic data) is not publicly available.

The abundance of emission sources across Indonesia means five potential industrial clusters were identified (Figure 1.5). The optimal source-sink matching and potential networks are located in the following basins:

1. Central Sumatra Basin
2. South Sumatra Basin
3. Northwest Java Basin
4. Northeast Java
5. East Java Basin

1.3.1.2.1. Central Sumatra

The Central Sumatra Basin has comparatively few domestic emissions and is predominantly onshore (Figure 1.5). The most prospective area of the basin is in the centre, near the hydrocarbon fields.

Suitability

The Central Sumatra Basin is categorised as ‘suitable’ for CO_2 storage, according to the Institute’s storage basin assessment tool. This assessment is based on:

- A moderate-sized (25,000-50000 km^2) basin with viable reservoir-seal pairs inferred from oil and gas fields.
- Published basin-scale storage assessments with resource estimates of hydrocarbon fields only. Field or data were not provided.
- Moderate exploration and development of hydrocarbon fields mean the subsurface geology is well-characterised.
- The legacy data associated with the mature hydrocarbon-producing basin reduces uncertainty in published resource estimates. Data associated with hydrocarbon exploration and production enables theoretical calculations of storage resources using real-world data.
- Indonesia does not host a public system to access subsurface data. However, data is accessible for approved users with nominal fees per data set.
- Indonesia has a regulatory framework to enable CCS.

Negative characteristics include:

- A convergent tectonic environment can increase the likelihood of major faulting, seismicity, and high geothermal gradient and pressure issues.
- Moderate exploration and development of hydrocarbon fields restricts assessments to producing areas.
- Assessed hydrocarbon fields are small size (<5 MtCO_2) or are shallow (<800 m)
- Published storage assessments have not reviewed saline formations.

Storage Resources

The basin is a mature hydrocarbon producer. According to the current analysis and data, all the studied fields are too shallow (<800 m) or had storage resource estimates of less than 5 MtCO_2. This finding varies from the 229 MtCO_2 estimated by Iskandar and Sofyan (2013), although the authors provided no information on the fields assessed and whether they used any screening criteria.

Due to the small and shallow hydrocarbon fields, CO_2 storage development in the basin will rely on saline formation storage. This analysis only acquired data for the Bekasap and Duri (Sihapas Group) with a P50 storage resource estimate of 6.4 GtCO_2. The formations are the major producing sandstones of the basins's oil fields. This infers viable reservoir-seal pairs. The Group extends across much of the basin, varying from 150-450 m thick (C. Caughey & T. C. Cavanagh, 1994).

The Central Sumatra Basin still requires the fundamental early stages of exploration and characterisation. Therefore, the basin presents a near to long-term (5+ years) opportunity for CO_2 storage in saline formations. As an onshore basin, the development of a site could have lower costs and be quicker to develop compared to an offshore Indonesian site.

Notably, the Central Sumatra Basin could potentially host international CO_2 from nearby sources in Singapore and the west coast of Malaysia. These are discussed below in the relevant sections.

1.3.1.2.2. South Sumatra Basin

The South Sumatra Basin is located under Sumatra Island, underlying the major city of Palembang.

Suitability

The South Sumatra Basin is categorised as 'highly suitable' for CO_2 storage, according to the Institute's storage basin assessment tool. This assessment is based on:

- A moderate-sized (25,000-50000 km^2) basin with viable reservoir-seal pairs inferred from oil and gas fields.
- Published basin-scale storage assessments on oil and gas fields and saline formations with resource estimates, but field/formation or data were not provided.
- Prolific exploration and development of hydrocarbon fields mean the subsurface geology is well-characterised.
- The legacy data associated with the mature hydrocarbon-producing basin reduces uncertainty in published resource estimates. Data associated with hydrocarbon exploration and production enables theoretical calculations of storage resources using real-world data.
- The mature hydrocarbon industry could provide access to legacy infrastructure such as pipelines, wells, platforms, etc.
- Indonesia does not host a public system to access subsurface data. However, data is accessible for approved users with nominal fees per data set.
- Indonesia has a regulatory framework to enable CCS.
- The basin is host to the planned Repsol Sakakemong CCS Facility. Pursuing a CCS Facility in the basin strongly indicates that an operator understands that the storage resources are available and commercially feasible.

Negative characteristics include:

- The basin is only moderately explored away from producing areas, reducing access to data and a complete understanding of the basin's storage potential.
- Published storage assessments have not reviewed saline formations in detail or provided data, including the formation name.

The basin is predominantly onshore, with a minor offshore component to the north of the island. The basin underlies a significant industrial emissions cluster. The basin's most prospective area is located in the onshore, central portion. The South Sumatra Basin has been thoroughly reviewed for CO_2 storage. The ADB (2013) assessed only this basin during their multi-national Southern East Asia study, finding it prospective for CO_2 storage.

Storage Resources

The basin is a mature oil and gas province. The basin hosts a few giant gas fields that could prove strong candidates for storage. The storage resources estimated in the hydrocarbon fields in this basin are the third highest in Indonesia, with a P50 total storage estimate of 426 $MtCO_2$. Over half of all storage is hosted in the gas fields of the Corridor PSC (184 $MtCO_2$) and Pendopo & Prabumulih PSC (107 $MtCO_2$). The total estimate is comparable to the 532 $MtCO_2$ estimate for hydrocarbon fields by the World Bank (World Bank, 2015) and 537 $MtCO_2$ by Hedriana et al. (2017). All authors noted that most fields could not host a commercial-scale

CCS facility due to their small size[1]. Based on the current analysis and data, there are limited CO_2 EOR-storage opportunities in the conventional oil fields of the South Sumatra Basin, with an additional oil recovery ranging from 0.4 to 2.6 MMbbl and net CO_2 storage resources of approximately 5.6 $MtCO_2$. This limitation is attributed to the small size of the oil fields.

The current analysis could not derive data for the saline formations of the South Sumatra Basin. The Batu Raja (Carbonate) and the Talang Akar (Sandstone) formations underlie much of the basin and are the reservoirs for hydrocarbon fields. The World Bank estimated a storage resource for unnamed saline formations in the South Sumatra Basin of 279-683 $MtCO_2$ (World Bank, 2015).

The basin represents early, near-term (5 years +) opportunities for storage. The significant industrial emissions would likely exhaust short-term prospects such as depleted hydrocarbon fields. More analysis of saline formations is required. The subsurface geology around the oil and gas fields is well-characterised in the onshore part of the basin. Subsurface data reduces uncertainty in storage assessments and improves the confidence of storage resource estimates.

1.3.1.2.3. Java Island

The island of Java represents an almost continuous collection of industrial emission clusters stretching west to east across the island.

Suitability

Three basins were identified on Java Island: Northeast Java and East Java were categorised as 'highly suitable' for CO2 storage, and Northwest Java was categorised as 'suitable' according to the Institute's storage basin assessment tool (). These basins present a robust source-sink matching across Java. The following positive factors include:

- Northwest and East Java basins are moderate-sized (25,000-50000 km^2) basins with viable reservoir-seal pairs inferred from oil and gas fields; the Northeast Java Basin is classified as large (over 50,000 km^2).
- Published basin-scale storage assessments with resource estimates of hydrocarbon fields only. Field or data were not provided.
- A comprehensive site scale analysis for the Northeast Java Basin is associated with the Gundih Pilot Project.

[1] Although there are no official standards on categorising a CO_2 storage site by its resource estimate (comparable to AAPG's Super Giant and Giant oil fields), generally, a storage site should host 20-40 years of a commercial CCS facility's CO_2 emissions. Therefore, at a minimum, a small site would have a total storage capacity of less than 20 $MtCO_2$, whereas a large site would be above 100 $MtCO_2$.

- Prolific exploration and development of hydrocarbon fields mean the subsurface geology is well-characterised.
- The legacy data associated with the mature hydrocarbon-producing basin reduces uncertainty in published resource estimates. Data associated with hydrocarbon exploration and production enables detailed assessments of storage resources. In this case, it is limited to the resources of the oil and gas fields within the basins, apart from the East Java Basin, which has saline formation data.
- Indonesia does not host a public system to access subsurface data. However, data is accessible for approved users with nominal fees per data set.
- Indonesia has a regulatory framework to enable CCS.
- The Northeast Java Basin has two CCS facilities planned by Pertamina – Jatibarang and Sukowati. In addition, the basin hosts the Gundih Pilot Plant. Pursuing a CCS Facility in the basin provides a strong indication that an operator understands that the storage resources are available and commercially feasible.

Negative characteristics include:

- The Northeast Java basin is a convergent tectonic environment that can increase the likelihood of major faulting, seismicity, and high geothermal gradient and pressure issues.
- The basins are only moderately explored away from producing areas, reducing access to data and a complete understanding of the basin's storage potential.
- Published storage assessments have not reviewed saline formations.

Storage Resources

North East Java Basin has an estimated P50 storage resource totalling 138 $MtCO_2$ across eight hydrocarbon fields, with 78 $MtCO_2$ storage resources available. This resource estimate of East Java and North West Java totals around 130 and 102 $MtCO_2$, respectively (Table 1.4). However, as seen in Figure 1.7, the storage potential in most of the Javanese basins' fields is less than 20 Mt CO_2, with some exceptions:

- North West Java hosts the two large gas fields in Jatibarang (P50- $M_{CO2\,net}$ ≅ 20 $MtCO_2$) and Subang (P50- $M_{CO2\,net}$ ≅ 82 $MtCO_2$).
- North East Java basin with three fields above 20 $MtCO_2$.
- East Java Basin has a field of around 96 $MtCO_2$.

East Java and North East Java have the highest CO_2 EOR-storage potentials amongst the studied Basins.

Comparable to other Indonesian basins, there is very little data on the saline formations of Java Island. This analysis found data on the Kujung Formation within the onshore East Java

Basin. The storage resource estimate is 8 $GtCO_2$ (P50) (Table 1.6). This formation is the main reservoir for a host of fields in the basin. The carbonate extends across much of the basin and is fair to good quality reservoir (porosity 7-32, permeability 1-1400 mD). The heterogeneous nature of carbonate reservoirs and the variation in reservoir data across different fields means there is low confidence in a cumulative resource estimate for Saline Formations in the Kujung Formation.

The small to moderate size of the hydrocarbon fields across Java Islands means saline formation represents the best opportunity to develop large CCS networks. Unfortunately, there is limited information on the saline formations of these basins. The existence of major oil and gas-producing fields across all basins infers that there are viable reservoir seal pairs across several different formations. The saline formations associated with these fields need to be explored further.

1.3.1.2.4. Kutei

The Kutei Basin was not selected in the source-sink matching exercise because the area hosts significantly fewer industrial emissions. However, this analysis shows the basin hosts the largest total hydrocarbon field potential of 698 $MtCO_2$ (Figure 1.6) and saline formation of 32 $GtCO_2$ (Table 1.6). Despite the area having comparatively fewer industrial sources than other places across Indonesia, several sources of CO_2 emissions are still associated with natural gas and petrochemical refining. The basin is planned to host the Pertamina Balikpapan CCS Facility.

1.3.1.3. Summary of storage deployment prospects, barriers, and issues

Indonesia is in the execution phase of the deployment of CCS, with multiple hydrocarbon companies progressing CCS facilities associated with natural gas development and hydrocarbon/ammonia production. The country now has a comprehensive national regulatory framework for CCS projects. The introduction of these regulations provides a strong indication that the government is supportive of CCS.

A unique challenge to central Sumatran and Java's industrial emission clusters is access to sufficient storage resources. According to the Institute's internal analysis, these clusters require gigatonne annual injection and storage rate. This rate of storage means significant investment and acceleration of storage development. Yet, Indonesia's storage potential remains largely unknown. For example, there are no public assessments of saline formations, and published analysis of hydrocarbon fields has no accompanying data. These two factors represent a significant barrier to developing storage resources and wider CCS deployment.

1.3.2. Malaysia

Malaysia has high prospects for multiple CCS networks, focussing on the offshore Malay-Tho Cho (herein 'Malay' and Sarawak basins. Malaysia's storage potential has been reviewed consistently for at least two decades. An extensive and mature oil and gas industry has enabled the characterisation of the subsurface geology in oil and gas basins.

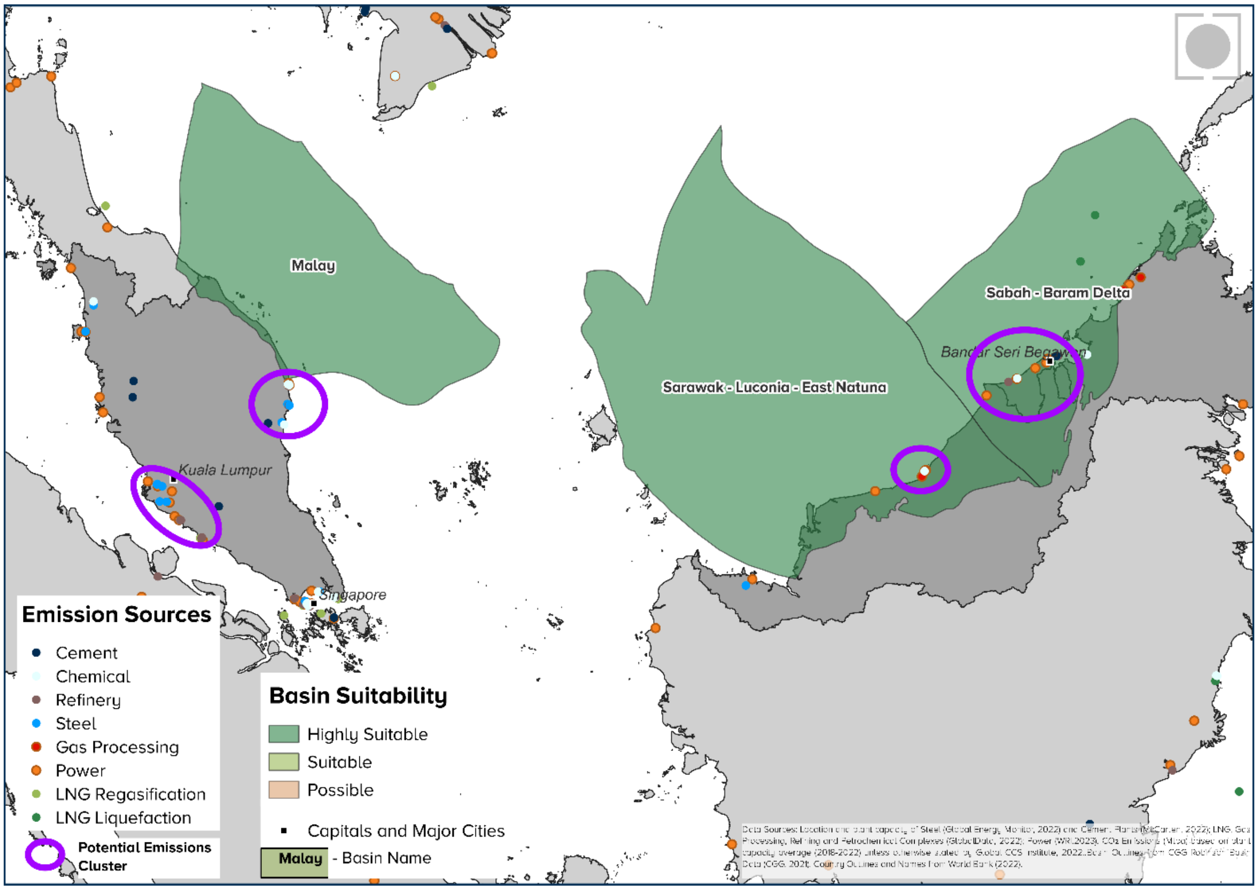
Petronas is building the Kasawari CCS Facility in the Sarawak Basin (Figure 1.1). Reservoir CO_2 from a high CO_2 (up to 25 mol%) gas field will be separated using membrane separation technology. CO_2 will be transported via a 138 km long subsea pipeline to a fixed offshore platform for injection into a depleted gas reservoir at the M1 field. Given the volume of CO_2 from the existing operation, other emission sources beyond Petronas' gas fields are unlikely to use the services of the Kasawari CCS.

Petronas is planning a second CCS operation in the Sarawak Basin, called Lang Lebah. Here, CO_2 from a high CO_2 field will be processed onshore and piped for offshore injection into a depleted gas field.

In addition, Petronas seeks agreements from third parties from dedicated CO_2 transport and storage networks. One such example is the Korean Sheperd CCS. The Korean consortium plans to capture CO_2 from industrial emissions in Korea for storage in Malaysian waters through Petronas.

In Malaysia, three emission clusters have been identified (Figure 1.8). In addition, there is the Singapore cluster (See Singapore below).

Figure 1.8. Emission Clusters and Storage Basins in Malaysia and Brunei



Note: This analysis categorises the Brunei part of the Sabah-Baram Delta Basin as 'Suitable'.
Source: GCCSI.

1.3.3. CO_2 Storage Resource Summary

The estimated CO_2 storage resources of oil and gas fields (Table 1.7; Figure 1.9; Figure 1.10), CO_2-EOR (Table 1.8), and saline formations (Table 1.9) are summarised below. Figure 1.9 shows the median (P50) cumulative net CO2 storage resources ($\boldsymbol{M_{CO2\ net}}$) across studied conventional oil and gas fields per basin. As observed in the figure, the majority of storage resources are provided by gas fields, with the Sarawak Basin having the highest net storage resources ($\boldsymbol{M_{CO2\ net}}$). Notably, the Sarawak Basin also boasts the highest available storage resources (Figure 1.9). Figure 1.10 displays the P50-net storage resources in the examined oil and gas fields. The figure reveals that half of the fields are relatively small, offering storage resources of less than 20 $MtCO_2$. This size constraint might render them unsuitable for average-sized, long-term commercial-scale CCS facilities. However, a more in-depth assessment of each field is necessary before making definitive conclusions.

Table 1.7. Malaysia: Estimated CO_2 Storage Resources in Hydrocarbon Fields

Basin	P50-Storage Available ($MtCO_2$)	P50-Storage Remaining ($MtCO_2$)	P50-Storage Net ($MtCO_2$)	Number of Gas Fields	Number of Oil Fields
Malay Basin	421.6	147.9	569.5	8	9
Sabah Basin	84.8	97.9	182.7	2	5
Sarawak Basin	783.9	236.6	1020.5	13	4
Total	**1290**	**482**	**1773**	**23**	**18**

Source: GCCSI.

Table 1.8. Malaysia: Estimated CO_2 Storage Resources in Oil Fields Assessed for CO_2 EOR-Storage

Basin	P50-Storage Available	P50-Storage Remaining	P50-Storage Net	Extra Oil Recovery (MMbbl) @RF5%	Extra Oil Recovery (MMbbl)-@RF30%
Malay Basin	14.88	4.86	19.74	3.4	20.3
Sabah Basin	30.37	17.46	47.84	6.4	38.1
Sarawak Basin	22.69	14.93	37.61	6.6	39.6
Total	**68**	**37**	**105**	**16**	**98**

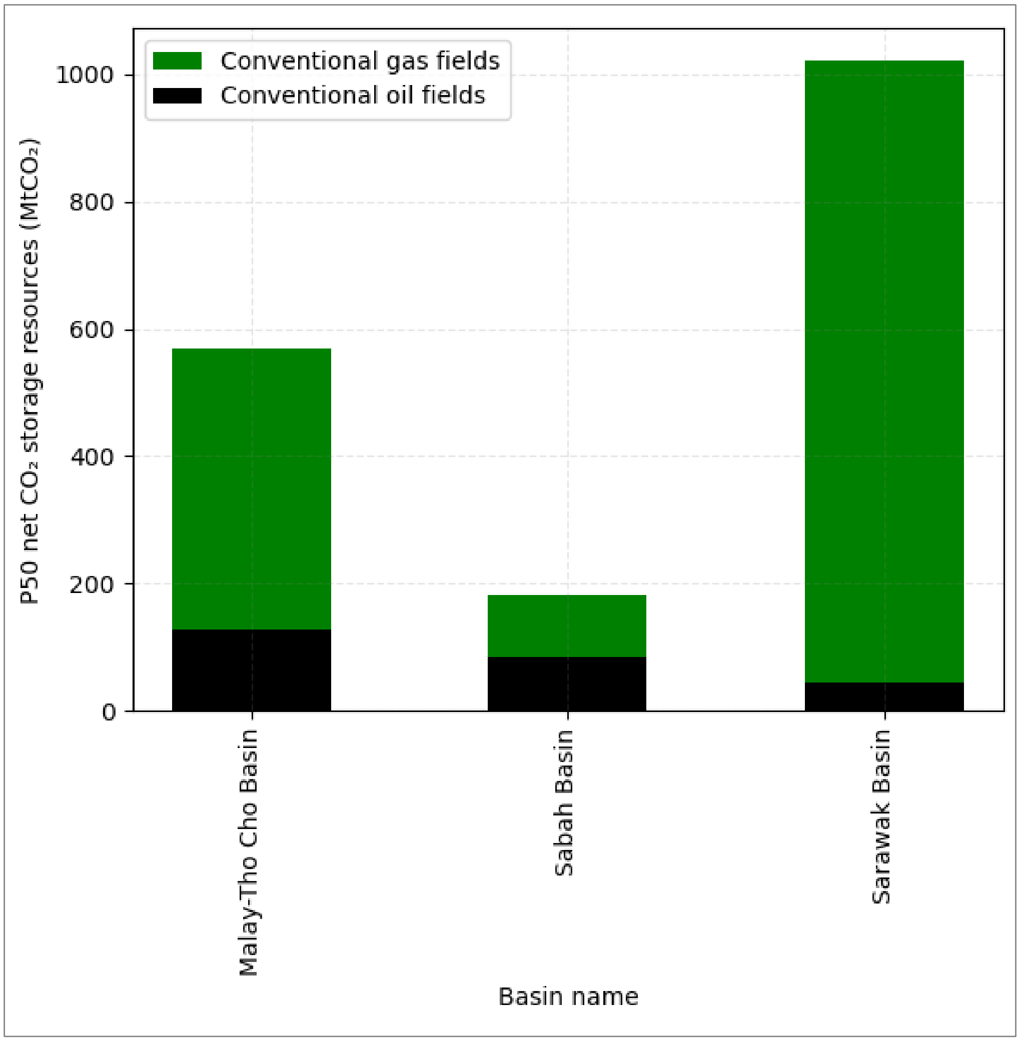
Source: GCCSI.

Table 1.9. Malaysia: Estimated CO_2 Storage Resources in Saline Formations

Basin	Formation(s)	P90 ($GtCO_2$)	P50 ($GtCO_2$)	P10 ($GtCO_2$)
Malay (Malaysia)	Sandstone below Upper Miocene intraformational seal	48	83	136
Sarawak	Carbonate below Middle-Upper Miocene regional marine shales	31	44	61
Total		**80**	**127**	**197**

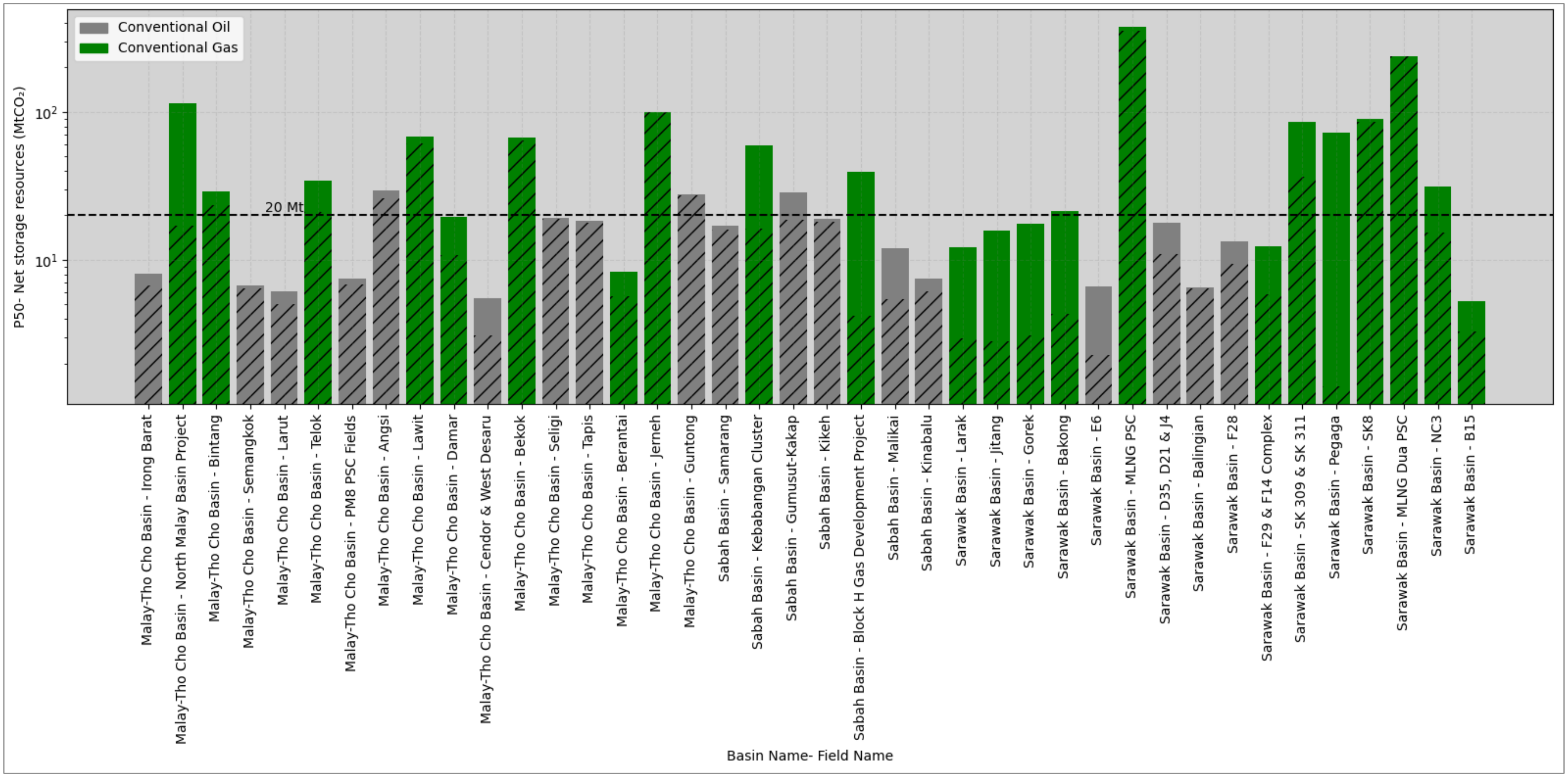
Note: the resources of the Malaysian part of the Sabah Basin were not completed due to a lack of data.
Source: GCCSI.

Figure 1.9. Cumulative P50 Net CO_2 Storage Resources in Studied Oil and Gas Fields per Basin Across Malaysia



Source: GCCSI.

Figure 1.10. P50 Net CO_2 Storage Resources of the Studied Oil and Gas Fields in the Malaysian Basins



Note: the available CO_2 storage resources are shown as a texture on the bars.
Source: GCCSI.

1.3.3.1. Prospective Basins with Potential Clusters

Malaysia has three key storage basins with a cluster of industrial emissions adjacent to a suitable storage basin (Figure 1.8) and significant storage resources in hydrocarbon fields and/or saline formations. The basins include:

1. Malay Basin
2. Sarawak Basin
3. Sabah Basin

1.3.3.1.1. Malay Basin (Thailand and Malaysian Waters)

The Malay Basin is located in the South China Sea, adjacent to Malaysia and Thailand. The basin is entirely offshore, in around 90-130 m water depths. There are two prospective areas in the basin: Thailand's portion in the north and the southeast of the basin in Malaysian waters. These areas are mature hydrocarbon-producing areas, predominantly gas and oil in the north and mainly oil in the southeast.

Suitability

The basin is categorised as 'highly suitable' for CO_2 storage, according to the Institute's storage basin assessment tool. This assessment is based on:

- A large (>50000 km^2) basin with viable reservoir-seal pairs inferred from multiple hydrocarbon fields.
- The extensive exploration and development of hydrocarbon fields mean the subsurface geology is well characterised.
- Published basin-scale storage assessments with resource estimates. Most studies focus on oil and gas fields, but some analyses also studied saline formations. Data on fields and formation in these studies was not provided or was very limited. A dynamic model with some limited injection data was also published.
- The legacy data associated with the mature hydrocarbon-producing basin reduces uncertainty in published resource estimates. Data associated with hydrocarbon exploration and production enables theoretical calculations of storage resources using real-world data.
- The mature hydrocarbon industry could provide access to legacy infrastructure such as pipelines, wells, platforms, etc., which could reduce timeframes to deployment and improve the economics of a CCS facility.
- The Thai part of the basin is the target of the PTTEP Arthit CCS Facility. Pursuing a CCS Facility in the basin provides a strong indication that an operator understands that the storage resources are available and commercially feasible.

Negative characteristics include:

- An offshore basin can increase an operation's costs and complexity.
- The high CO_2 content of gas fields (up to 70 mol%; Raza et al., 2018, and references therein) can compete for pore space with other industrial sources onshore.
- Malaysia has no national regulatory regime, with a regulatory framework limited to Sarawak.
- Malaysia does not host a public system to access subsurface data.

Storage Resources

The Malay Basin (Thai and Malay parts) is highly suitable; this conclusion is based on a mature hydrocarbon industry and published storage analysis associated with developing hydrocarbon fields. The Malay Basin hosts 570 $MtCO_2$ in hydrocarbon fields, with the majority available (422 $MtCO_2$) due to the region's long production history. Figure 1.10 shows two large gas fields (Jerneh and North Malay) in the basin that offer P50-net CO_2 storage resources higher than 100 $MtCO_2$. However, the Jerneh gas field is largely depleted out of these two and could host a significant CCS network. The Jerneh gas field has a water depth of approximately 60 m and was discovered in 1969 (Fahmi, 2007). The field comprises coastal plain to tidal/shallow marine sandstones of the Upper Miocene seismic group D and E reservoirs (Bintang and Jerneh Formations, respectively) in the Malay Basin (Madon & Council, 2016). Porosity ranges from 10 to 25 %, and permeability can be up to 1000 mD in Jerneh Field sandstones (Bishop, 2002; Madon & Council, 2016).

A multi-nation, regional analysis of CO_2 storage associated with gas fields found an estimated storage potential of 602 $MtCO_2$ in the Malay Basin (CO2CRC, 2010). This estimate is comparable to the current assessment. Furthermore, a subsequent review of Thailand's oil and gas fields in the Malay Basin estimated a storage resource of 601 $MtCO_2$ (Choomkong et al., 2017).

Based on the current analysis and data, there are limited CO_2 EOR-storage opportunities in the studied conventional oil fields of the Malay Basin, with an additional oil recovery ranging from 3.4 to 20.3 MMbbl and P50 net CO_2 storage resources of approximately 19.7 $MtCO_2$.

A total storage potential of 83 $GtCO_2$ (P50) was estimated for a saline formation in the Malay Basin. The sandstones below the Upper Miocene intraformational seal in the Malay Basin (Groups D and E) belong to the Bekok and Tapis formations, where the data was derived. The deposits are coastal plains and shallow marine sandstones (Ramli, 1988). Tapis Formation porosity ranges from 10 to 30%, and permeability ranges from 1 to 1000 mD (Ramli, 1988), making it a suitable target for CO_2 storage.

Junin and Hasbollah (2016) estimated that the same saline formations (Groups D and E in their study) in the same area of the Malay Basin could host a total of 84 $GtCO_2$. Within

Thailand's part of the Malay Basin, a dynamic simulation on Pleistocene fluvial sandstones that dominate much of the region found an injection rate of 0.3-1.3 Mtpa CO_2.

The Malay Basin still requires the fundamental early stages of exploration and characterisation. Therefore, the basin presents a near-term (5 years +) opportunity for CO_2 storage. However, Thailand and Malaysia's national oil companies are pursuing CCS operations in the basin and incorporating CCS networks into their long-term plans.

1.3.3.1.2. Sarawak

The Sarawak Basin is west of Malaysian Borneo in the South China Sea. The basin is predominantly offshore, with water depths ranging from very shallow (50 m) to 500 m. This large basin's most prospective storage area is where previous studies focused on the re-injection of CO_2 from gas fields. That area is in the centre of the SW Luconia Sub-province, around 300 km from the Sarawak region.

Suitability

The basin is categorised as 'highly suitable' for CO_2 storage, according to the Institute's storage basin assessment tool. This assessment is based on:

- A large (>5,0000 km^2) basin with viable reservoir-seal pairs inferred from multiple hydrocarbon fields.
- Published basin-scale storage assessments with resource estimates. Most studies focus on oil and gas fields, but few focus on saline formations. Data on fields and formation in these studies was not provided or was very limited. Several site-scale studies evaluating the potential for storage in depleted fields adjacent to planned high CO_2 gas field developments were also completed.
- The extensive exploration and development of hydrocarbon fields mean the subsurface geology is well characterised.
- The legacy data associated with the mature hydrocarbon-producing basin reduces uncertainty in published resource estimates, as hydrocarbon data enables detailed assessments of storage resources, such as numerical studies, in the oil and gas fields within the basins.
- The mature hydrocarbon industry could provide access to legacy infrastructure such as pipelines, wells, platforms, etc., which could reduce timeframes to deployment and improve the economics of a CCS facility.
- The basin will host two planned CCS Facilities, Petronas Kasawari and PTTEP Lang Lebah. Pursuing a CCS Facility in the basin provides a strong indication that an operator understands that the storage resources are available and commercially feasible.
- A regulatory framework is limited to Sarawak.

Negative characteristics include:

- An offshore basin can increase an operation's costs and complexity.
- The high CO_2 content of gas fields (up to 70 mol%; Raza et al., 2018, and references therein) can compete for pore space with other industrial sources onshore.
- Malaysia does not host a public system to access subsurface data

Storage Resources

The Sarawak Basin is highly suitable; this conclusion is based on a mature hydrocarbon industry and published storage analysis associated with developing hydrocarbon fields. The basin hosts a total of 1 $GtCO_2$ in hydrocarbon fields, with the majority available (784 $MtCO_2$) due to the long production history of the region (Table 1.7). The field with the largest CO_2 storage resources in the basin is the MLNG PSC (Figure 1.10), which comprises five gas fields totalling 374 $MtCO_2$. The data for this assessment did not separate the five fields individually.

The Sarawak Basin offers the highest CO_2 EOR-storage opportunities between the studied basins, with an additional oil recovery ranging from 7 to 40 MMbbl and P50 net CO_2 storage resources of approximately 38 $MtCO_2$.

This analysis has found the saline formations in the Sarawak Basin are Middle-Upper Miocene carbonates and sandstones (Cycles IV, V) with a storage resource estimate of 44 $GtCO_2$ (P50) (Table 1.6). These formations are around 1-1.5 km in depth, with an average porosity of 20% and total thicknesses above 900 m, extending for over 150 km (Junin & Hasbollah, 2016). Junin and Hasbollah (2016) found a storage resource of between 56 $GtCO_2$ in the same formations of this analysis using the same methodology.

Other published studies have identified multiple reservoir-seal pairs, the primary target being carbonate reefs sealed by regional Middle-Upper Miocene regional marine shales. Several studies have focused on storage in carbonate reefs in the Sarawak Basin. These studies' primary driver is the development of high CO_2 (up to 70 mole%) gas fields in the same basin (Raza et al., 2017). A second set of studies recently focused on the Tangga Barat cluster of fields. Presently operated by Petronas, the fields have high CO_2 content (40 mole%) (Sukor et al., 2020). The storage operation would focus on the same formation as the gas field, with injection down-dip from the field.

When considering CCS network development opportunities, the Sarawak Basin still requires the characterisation of storage sites, mainly focussing on saline formations. Hence, the basins present a near-term (5-10 years) opportunity for CO_2 storage. However, developing a CCS facility associated with high CO_2 gas field development could be the anchor facility for a wider CCS network of emission sources, potentially importing from international sources due to the high resource estimate versus local emissions.

1.3.3.1.3. Sabah - Baram Delta

The Sabah - Baram Delta has a single industrial emissions cluster of natural gas processing (including LNG), petrochemical and power generation (Figure 1.8). In addition, the gas content of the basin's fields contains up to 80 mol% CO_2 (CO2CRC, 2010). Therefore, the reservoir CO_2 produced from those fields could be the main focus of domestic CO_2 storage operations in Malaysia.

Suitability

The Malaysian part of the basin is categorised as 'highly suitable' for CO_2 storage in the Malaysian portion, according to the Institute's storage basin assessment tool. This assessment is based on:

- A large (>50,000 km^2) basin with viable reservoir-seal pairs inferred from multiple hydrocarbon fields.
- The extensive exploration and development of hydrocarbon fields mean the subsurface geology is well characterised.
- The legacy data associated with the mature hydrocarbon-producing basin reduces uncertainty in published resource estimates. Data associated with hydrocarbon exploration and production enables theoretical calculations of storage resources using real-world data.
- The mature hydrocarbon industry could provide access to legacy infrastructure such as pipelines, wells, platforms, etc., which could reduce timeframes to deployment and improve the economics of a CCS facility.
- A regulatory framework is limited to Sarawak.

Negative characteristics include:

- An offshore basin can increase an operation's costs and complexity.
- The high CO_2 content of gas fields (up to 70 mol%; Raza et al., 2018, and references therein) can compete for pore space with other industrial sources onshore.
- Malaysia does not host a public system to access subsurface data

The Malay portion of the basin is categorised higher than the Brunei portion because of its:

- Greater size
- Previous published storage studies and resource estimates
- Accessibility (regulations in place)

Storage Resources

The Malaysia part of the Sabah - Baram Delta Basin's hydrocarbon fields is estimated at 182

$MtCO_2$ (Total), with 84 $MtCO_2$ available now (Table 1.7). Only one field exceeds 20 $MtCO_2$, the Kebabangan Field (Figure 1.10).

1.3.3.2. Summary of Storage Deployment Prospects, Barriers, and Issues

- Malaysia hosts three highly suitable basins (including the Sabah Basin, which is both Malaysia and Brunei) in the region, with significant resources in hydrocarbon fields and saline formations with limited adjacent domestic emissions, even if considering the emissions of the Kuala Lumpur cluster.
- Malaysia lacks a comprehensive national CO_2 storage resource atlas, with limited information on saline formations.
- The development of high CO_2 content gas fields in offshore Malaysia enables the development of CCS networks with natural gas processing as the anchor facility.
- While Malaysia features several basins highly suitable for CO_2 storage (Malay, Sarawak, Sabah), only one state (Sarawak) has a CCS-specific legal and regulatory framework.
- Beyond the offshore potential of the Sabah, Sarawak and Malay basins, there is limited opportunity for the cluster of emissions near Kuala Lumpur. The nation will unlikely seek storage in Indonesia even though storage exists adjacent to the emissions sources. Accessing the Malay Basin's resources is the only likely potential for the KL cluster.

1.3.4. Brunei

Brunei has one basin for storage characterisation, the Sabah-Baram Delta Basin Malaysian Borneo in the South China Sea (Figure 1.8). The basin is predominantly offshore, with water depths ranging from very shallow (50 m) to 2,000 m. The prospective area is the nearshore portion of the basin, which hosts a significant hydrocarbon production along the length of Brunei and Malaysian Borneo.

1.3.4.1. CO_2 Storage Resource Summary

The estimated CO_2 storage resources of oil and gas fields (Table 1.10; Figure 1.11), CO_2-EOR (Table 1.11) and saline formations (Table 1.12) are summarised below. Figure 1.11 displays the P50-net storage resources in the examined oil and gas fields.

Table 1.10. Brunei: Estimated CO_2 Storage Resources in Hydrocarbon Fields

Basin	P50-Storage Available ($MtCO_2$)	P50-Storage Remaining ($MtCO_2$)	P50- Storage Net ($MtCO_2$)	Number of Gas Fields	Number of Oil Fields
Baram Delta	560.7	18.6	579.3	4	3

Source: GCCSI.

Table 1.11. Brunei: Estimated CO_2 Storage Resources in Oil Fields Assessed for CO_2 EOR Storage

Basin	P50-Storage Available	P50-Storage Remaining	P50-Storage Net	Extra Oil Recovery (MMbbl) @RF5%	Extra Oil Recovery (MMbbl) - @RF30%
Baram Delta	186.35	13.52	199.81	13.6	81.7

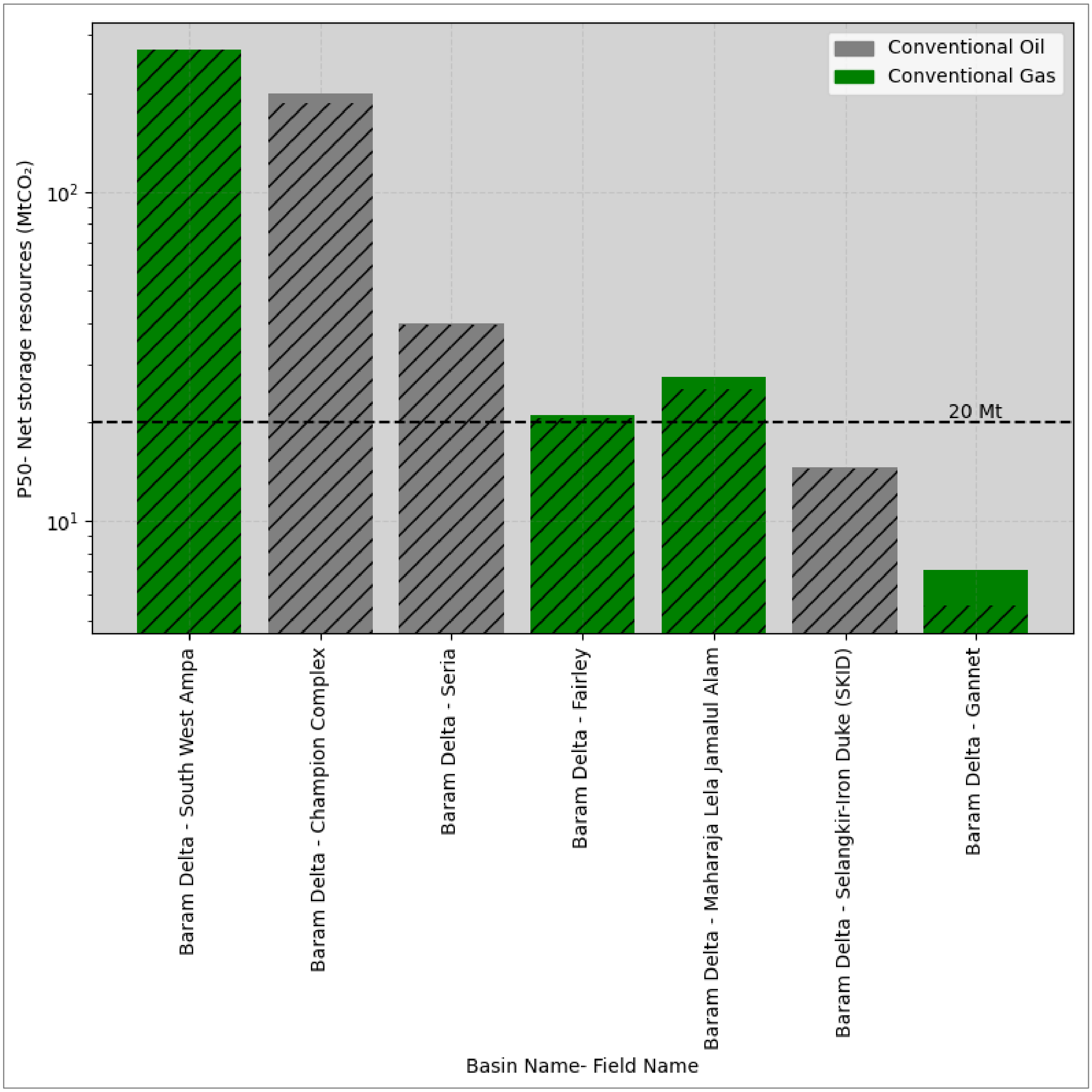
Source: GCCSI.

Table 1.12. Brunei: Estimated CO_2 Storage Resources in Saline Formations

Basin	Formation(s)	P90 ($GtCO_2$)	P50 ($GtCO_2$)	P10 ($GtCO_2$)
Sabah - Baram Delta	Baram Fluvial-Deltaic System sands	13	18	25

Source: GCCSI.

Figure 1.11. P50- Net CO_2 Storage Resources of Brunei's Studied Oil and Gas Fields



Note: The available CO2 storage resources are shown as a texture on the bars.
Source: GCCSI

1.3.4.2. Prospective Basins with Potential Clusters

1.3.4.2.1. Sabah - Baram Delta

The Sabah - Baram Delta has a single industrial emissions cluster of natural gas processing (including LNG), petrochemical and power generation (Figure 1.8). In addition, the gas content of the basin's fields contains up to 80 mol% CO_2 (CO2CRC, 2010). Therefore, the reservoir CO_2 produced from those fields could be the focus of domestic CO_2 storage operations in Brunei.

Suitability

The Brunei part of the basin is categorised as 'suitable' for CO_2 storage, according to the Institute's storage basin assessment tool. This assessment is based on:

- A moderate-sized (25,000-50000 km^2) basin with viable reservoir-seal pairs inferred from oil and gas fields.
- The extensive exploration and development of hydrocarbon fields mean the subsurface geology is well characterised.
- The legacy data associated with the mature hydrocarbon-producing basin reduces uncertainty in published resource estimates. Data associated with hydrocarbon exploration and production enables theoretical calculations of storage resources using real-world data.
- The mature hydrocarbon industry could provide access to legacy infrastructure such as pipelines, wells, platforms, etc., which could reduce timeframes to deployment and improve the economics of a CCS facility.

Negative characteristics include:

- An offshore basin can increase an operation's costs and complexity.
- The high CO_2 content of gas fields (up to 80 mol%; (CO2CRC, 2010) can compete for pore space with other industrial sources onshore.
- Brunei does not host a public system to access subsurface data
- No Brunei-specific published storage assessments with resource estimates. Brunei has only been included in global analyses of oil and gas fields.
- Brunei has no national regulatory regime.

Storage Resources

The Bruneian part of the Sabah - Baram Delta Basin's hydrocarbon fields is estimated at 579 $MtCO_2$ (Total), with 560 $MtCO_2$ available now (Table 1.10). The South West Ampa gas field is situated in less than 60 m of water depth and was discovered in 1963. The South West Ampa Field is assessed to possess 269.9 Mt of available CO_2 storage resources and 0.26 Mt of remaining CO_2 storage resources, resulting in a total CO_2 storage resource base of 270.16 Mt (Figure 1.11). These data indicate a significant level of depletion in the field, making it a potential strong candidate for average-sized, long-term commercial-scale CCS facilities in Brunei and the broader region. Nevertheless, a thorough field analysis is imperative to evaluate the impacts of geological complexities, such as reservoir compartmentalisation, on storage resources and injectivity. Following the South West Ampa Field, the Champion Complex offers the second-largest storage resources in the country, with net storage resources of around 200 $MtCO_2$, out of which 186 $MtCO_2$ is already available for storage

(Figure 1.11).

Regarding CO_2-EOR, there is a potential opportunity in the Champion Complex, presenting a range of additional oil recovery from approximately 6.4 to 38.1MMbbl, coupled with P50 net CO_2 storage resources of around 47.8 $MtCO_2$ (Table 1.8). Further detailed analysis of the fields is essential before making definitive conclusions.

The CO_2 storage resources of saline formations of Baram Fluvial-Deltaic System sands are estimated to be around 18 $GtCO_2$ (P50) (Table 1.12). The Baram Fluvial-Deltaic System comprises several sequences of Neogene clastic deposits ranging in thickness from 1,000 to 3,000 m offshore Brunei (Rijks, 2014). The Baram Fluvial-Deltaic System sands (Cycle V) feature porosities averaging 20 % and permeabilities averaging 980 mD, making it a suitable target for CO_2 storage (CO2CRC, 2010).

1.3.4.3. Summary of Storage Deployment Prospects, Barriers, and Issues

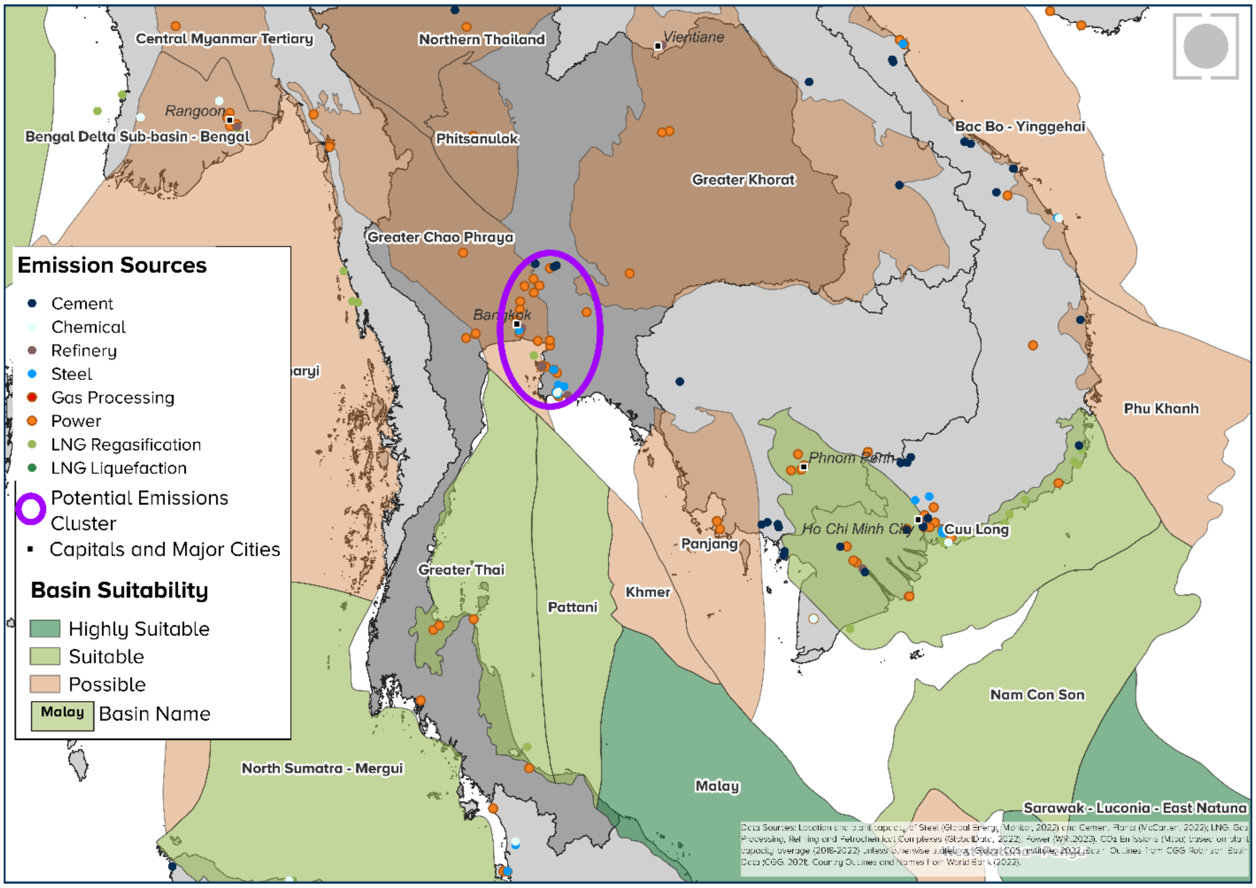
- Brunei hosts significant resources in hydrocarbon fields and saline formations in a highly suitable basin with limited domestic emissions.
- Detailed analysis of the South West Ampa Field and Champion Complex is essential for unlocking their CO_2 storage resources.
- Brunei could rapidly deploy CO_2 storage operations to enable a domestic CCS industry and the international import of CO_2. A CCS roadmap with CO_2 storage characterisation and detailed site scale assessment would support these opportunities.
- Brunei lacks a CCS-specific legal and regulatory framework and CCS-specific domestic policies or incentives.

1.3.5. Thailand

Thailand has high prospects for multiple CCS networks, with CO_2 transport and storage operations focussing on the offshore basins in the Gulf of Thailand. The CO_2 storage potential in Thailand has been reviewed in the literature over the past two decades. Subsequently, there is a moderate understanding of Thailand's storage potential.

PTTEP is developing the Arthit CCS Facility near the boundary of the Malay and Pattani basins. This facility, currently under development, will reduce emissions from gas fields with high CO_2 concentrations. There is no indication of expanding this facility beyond the reservoir CO_2. Also, PTTEP is exploring opportunities to build a CCS Network for industries in Rayong and Chonburi provinces. However, there is no public information on the storage portion of this network. One significant emission cluster in Thailand covers several hundreds of kilometres and incorporates Bangkok, south of the Gulf of Thailand (Figure 1.12).

Figure 1.12. Thailand's Emission Clusters and Storage Basins



Source: GCCSI.

1.3.5.1. CO_2 Storage Resource Summary

The estimated CO_2 storage resources of oil and gas fields (Table 1.13; Figure 1.13; Figure 1.14) and saline formations (Table 1.14) are summarised below. No suitable oil fields meeting the defined criteria for CO_2 EOR storage were identified in this study. This is attributed to the small size of the studied fields. Figure 1.13 shows the median (P50) cumulative net CO_2 storage resources ($M_{CO2\ net}$) across studied conventional oil and gas fields per basin. As observed in the figure, the majority of storage resources are provided by gas fields, with the Pattani Basin having the highest net storage resources ($\boldsymbol{M_{CO2\ net}}$). Notably, the Pattani Basin also boasts the highest available storage resources (Table 1.13; Table 1.14). Figure 1.14 displays the P50-net storage resources in the examined oil and gas fields. The figure reveals that half of the fields are relatively small, offering storage resources of less than 20 $MtCO_2$. This size constraint might render them unsuitable for average-sized, long-term commercial-scale CCS facilities. However, a more in-depth assessment of each field is necessary before making definitive conclusions.

Table 1.13. Thailand: Estimated CO_2 Storage Resources in Hydrocarbon Fields

Basin	P50- Storage available ($MtCO_2$)	P50- Storage remaining ($MtCO_2$)	P50- Storage net ($MtCO_2$)	Number of gas fields	Number of oil fields
Khorat Plateau Basin	16.9	8.0	24.9	2	0
Malay Basin	211.2	160.3	371.5	3	0
Pattani Basin	414.3	182.8	597.0	19	2
Phitsanulok Basin	26.9	3.3	30.2	0	1
Total	**669**	**354**	**1024**	**24**	**3**

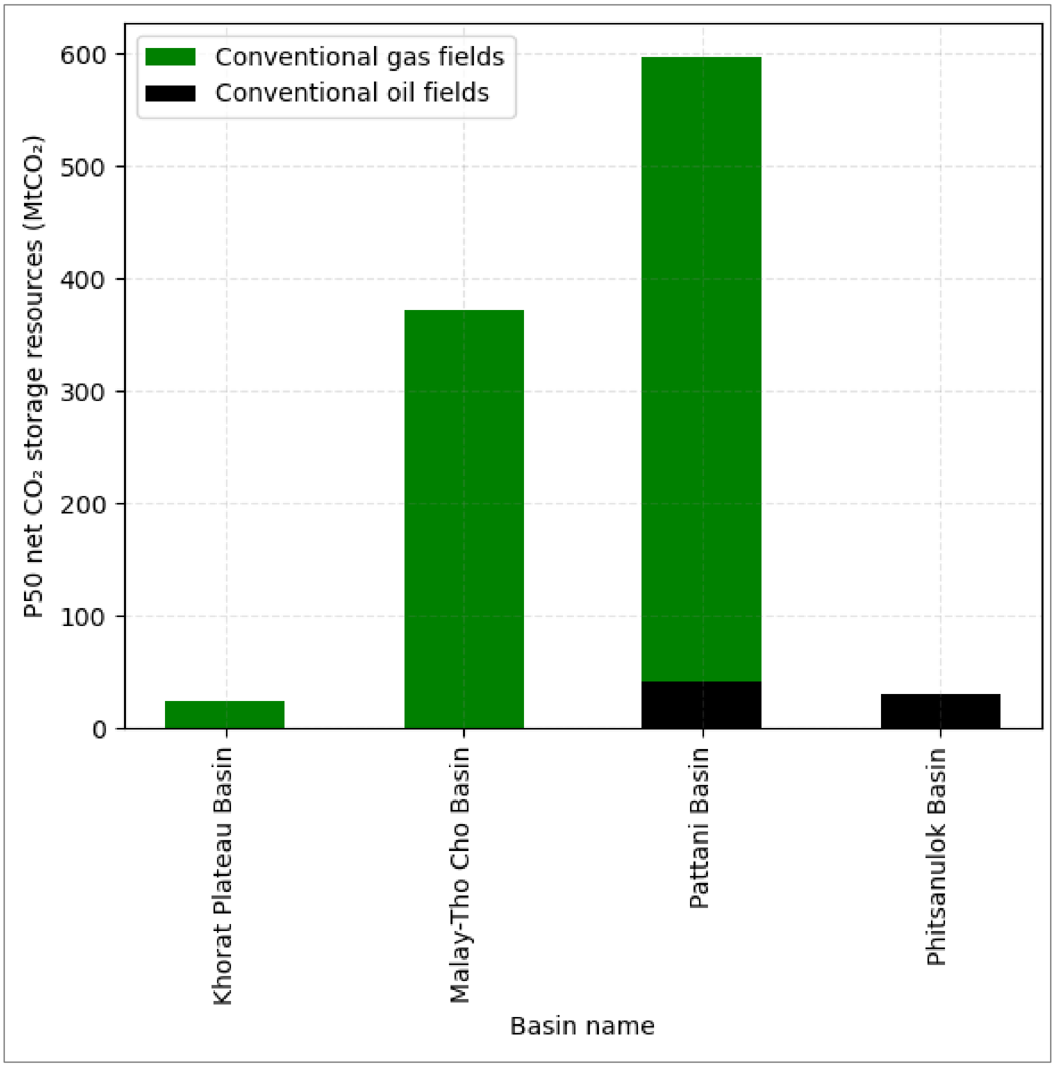
Source: GCCSI.

Table 1.14. Thailand: Estimated CO_2 Storage Resources in Saline Formations

Basin	Formation(s)	P90 ($GtCO_2$)	P50 ($GtCO_2$)	P10 ($GtCO_2$)
Pattani	Bekok, Tapis, Pulai	9	13	18
Malay (Thailand)	Sandstone below Upper Miocene intraformational seal	1.5	2	4
Total		**11**	**15**	**22**

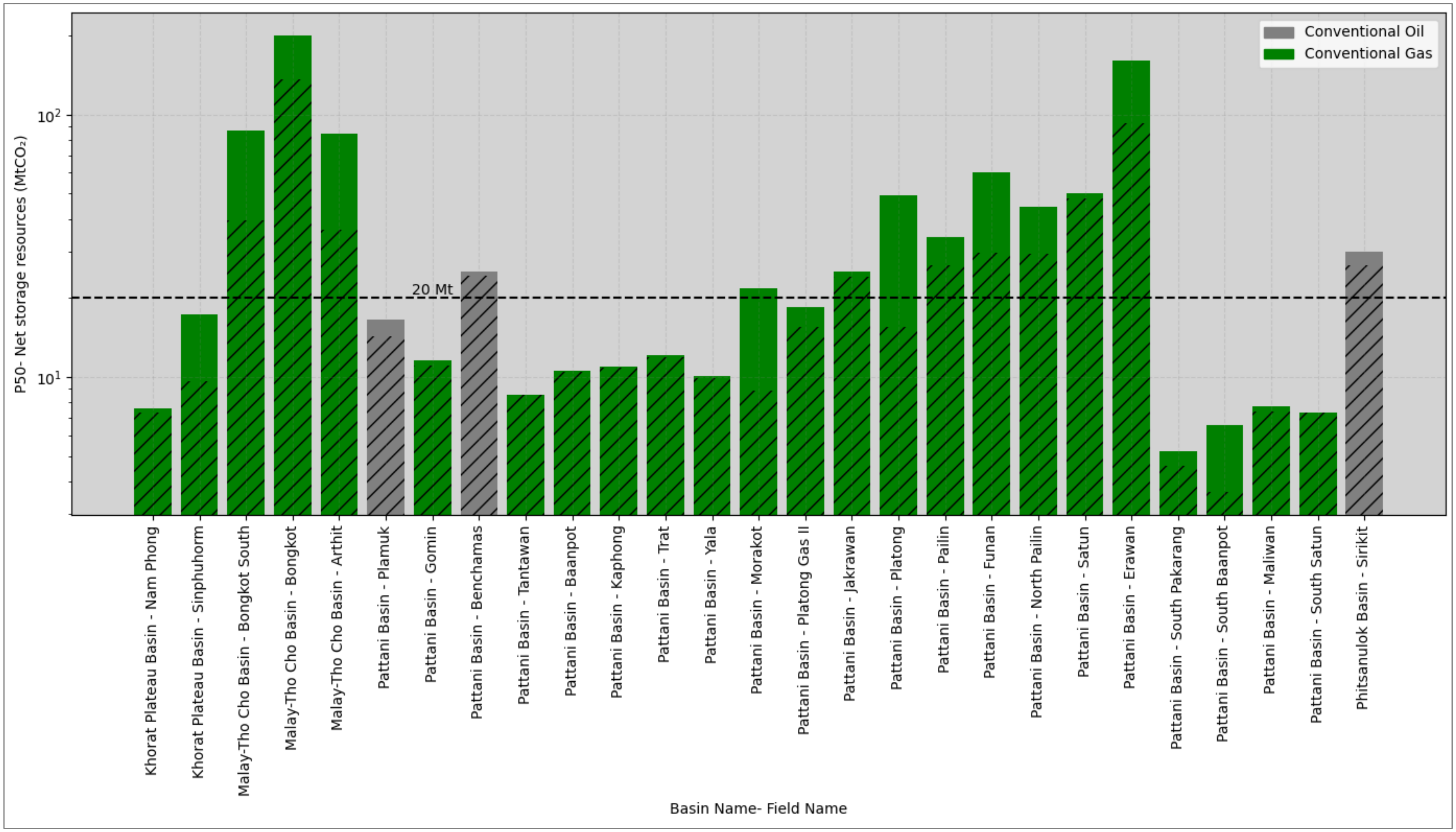
Source: GCCSI.

Figure 1.13. Cumulative P50 CO_2 Storage Resources in Studied Oil and Gas Fields per Basin Across Thailand



Source: GCCSI.

Figure 1.14. P50-Net CO_2 Storage Resources of the Studied Oil and Gas Fields in the Basins Across Thailand



Note: the available CO_2 storage resources are shown as a texture on the bars.
Source: GCCSI.

1.3.5.2. Prospective Basins with Potential Clusters

Thailand has two key storage basins with source-sink matching (Figure 1.12). The basins include:

- Malay
- Pattani

According to the Institute's Storage basin assessment tool, the Pattani Basin was assessed as 'suitable' for CO_2 storage. The suitability of the Malay Basin was previously discussed in the 'Malaysia' section; hence, it will not be repeated here.

1.3.5.2.1. Pattani

The Pattani Basin is in the Gulf of Thailand, adjacent to Thailand. The basin is entirely offshore in shallow water depths. The central portion of the basin is the most prospective, inferred from multiple hydrocarbon fields and the distribution of saline formations.

Suitability

The basin is categorised as 'suitable' for CO_2 storage, according to the Institute's storage basin assessment tool. This assessment is based on:

- A moderate-sized (25,000-50,000 km^2) basin with viable reservoir-seal pairs inferred from oil and gas fields.
- Published basin-scale storage assessments with resource estimates of hydrocarbon fields and saline formations. Field or data were not provided.
- The extensive exploration and development of hydrocarbon fields mean the subsurface geology is well characterised.
- The legacy data associated with the mature hydrocarbon-producing basin reduces uncertainty in published resource estimates. Data associated with hydrocarbon exploration and production enables theoretical calculations of storage resources using real-world data.
- The mature hydrocarbon industry could provide access to legacy infrastructure such as pipelines, wells, platforms, etc., which could reduce timeframes to deployment and improve the economics of a CCS facility.
- PTTEP are planning a CCS network in Thailand with storage in the Pattani Basin. Pursuing a commercial CCS Facility in the basin is a strong indicator of a viable storage resource and commercial opportunity for CCS.

Negative characteristics include:

- An offshore basin can increase an operation's costs and complexity.
- Thailand has no national regulatory regime.
- Thailand does not host a public system to access subsurface data.

Storage Resources

The Pattani Basin hosts an estimated storage resource totalling 570 $MtCO_2$ in hydrocarbon fields, with the majority available (597 $MtCO_2$) due to the region's long production history. As seen in Figure 1.14, conventional gas fields offer the majority of the storage resources in the basin, and most of these resources are already available. The Erawan gas field offers the highest CO_2 storage resources amongst the fields in the basin. As discussed earlier, no suitable oil fields meeting the defined criteria for CO_2 EOR storage were identified in this study. This is attributed to the small size of the studied fields.

The ADB (2013) also assessed known hydrocarbon traps in 10 of 94 sedimentary basins of Thailand. The top three ranked oil and gas fields have a combined estimated storage resource of 350 $MtCO_2$ ADB. The report also identified (but did not specifically name) two EOR prospects.

The Pattani Basin has CO_2 storage potential in Cenozoic sediments for saline formation storage, including multiple reservoirs and intraformational seals. The Miocene-aged Bekok, Tapis, and Pulai formations were estimated to host storage resources of 13 $GtCO_2$ (P50). This estimate is comparable to the ADB's multi-national assessment that estimated a total theoretical storage potential of around 10 $GtCO_2$ storage resource (ADB, 2013). However, the basin is geologically complex. Accumulations of the oil and gas fields in the basin are known to be volumetrically small as individual reservoirs due to the fluvial depositional nature of the reservoirs and intense faulting.

1.3.5.2.2. Khorat, Greater Choa Phraya and Phitsanulok basins

The onshore basins of Thailand, the Khorat, Greater Choo Phraya and Phitsanulok basins, have not been reviewed in this analysis due to a lack of published studies on their CO_2 storage potential. All basins have been categorised as possible for storage. The P50 hydrocarbon resource estimates of the Khorat and Phitsanulok are 25 (2 gas fields) and 30 $MtCO_2$ (1 oil field) (Table 1.13). The Greater Choa Phraya Basin had no hydrocarbon fields for analysis. Therefore, storage deployment will focus on saline formations. A basic mapping and characterisation analysis of the saline formations of these basins is critical, given their proximity to emission sources in Bangkok and the surrounding areas. Critically, onshore CO_2 storage operations generally cost less and have less complexity than offshore operations.

1.3.5.3. Summary of storage deployment prospects, barriers, and issues

- Thailand lacks a modern, comprehensive national CO_2 storage resource atlas. A particular focus should be on the Khorat, Greater Choo Phraya and Phitsanulok basins onshore.
- The Malay and Pattani basins require targeted site-scale characterisation analysis to understand the hydrocarbon fields and associated saline formations. Hence, the basins present a near to long-term (5-10 years +) opportunity for CO_2 storage.
- Thailand lacks a CCS-specific legal and regulatory framework and CCS-specific domestic policies or incentives. However, the national oil company, PTTEP, are proactive in CO_2 storage deployment, which may drive changes in the regulatory and policy frameworks.

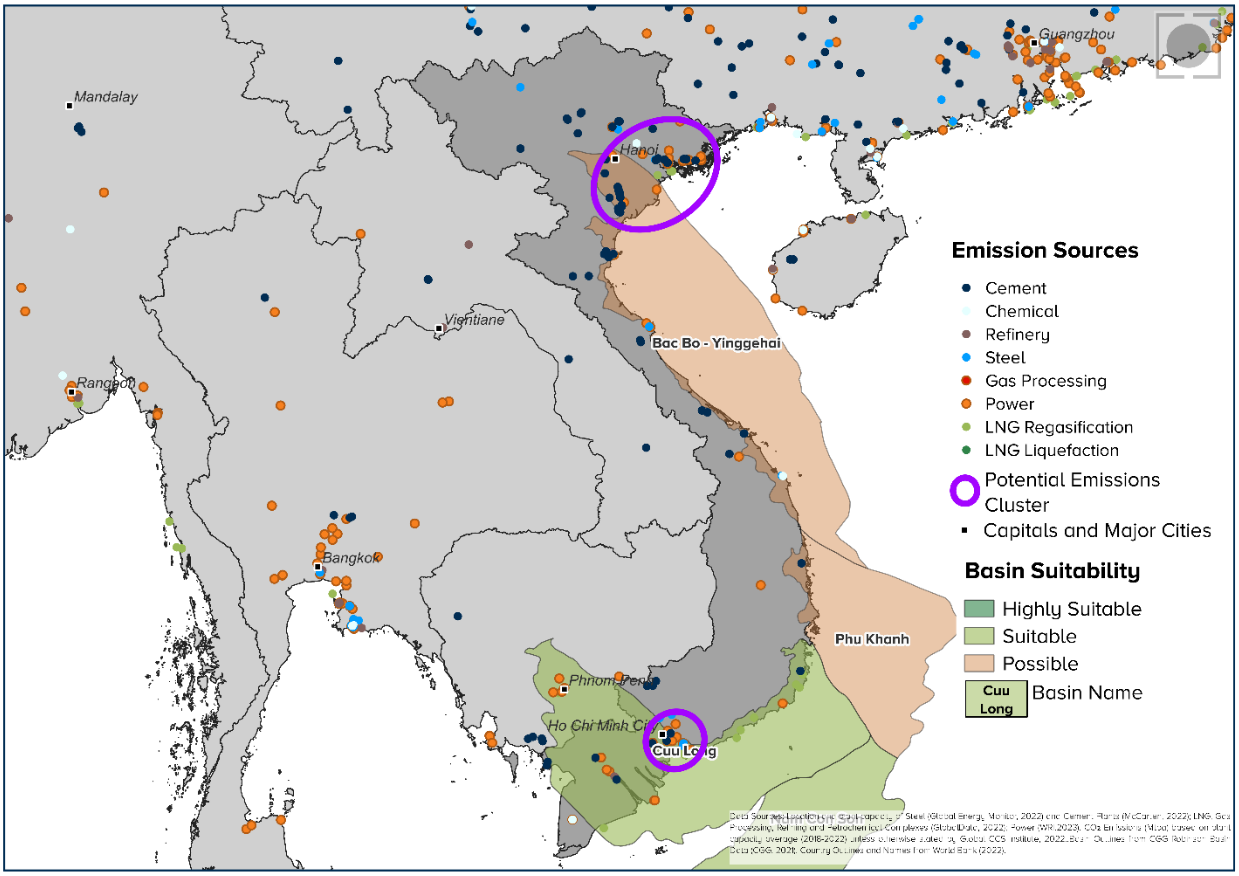
1.3.6. Viet Nam

Viet Nam has the geological potential to host a significant CCS industry. However, their lack of storage development means their prospects of hosting CCS networks in the short to medium term are unlikely.

Experience in CO_2 injection and storage includes two pilot CO_2-EOR operations, White Tiger (Bach Ho) and Aurora (Rang Dong). The White Tiger CO_2-EOR operation was the first pilot project in Southeast Asia and possibly the only CO_2 injection project to date. The details of the operation are unknown. However, according to Ha-Duong & Nguyen-Trinh (2017), a feasibility study by Petro Viet Nam in collaboration with Mitsubishi Heavy Industries estimated an injection rate of between 4.6 – 7.4 Mtpa. The timeframe for this injection rate and total storage capacity was not recorded.

The White Tiger CCS project applied for funding under the Clean Development Mechanism (CDM) of the UNFCCC. However, CCS projects were not included in the funding. Another small pilot CO_2 injection project is in the Song Hong Basin and has also been presented at forums (Hieu, 2016).

Figure 1.15. Viet Nam's Emission Clusters and Storage Basins



Source: GCCSI

1.3.6.1. CO_2 Storage Resource Summary

The estimated CO_2 storage resources of oil and gas fields (Table 1.15; Figure 1.16; Figure 1.17), CO_2-EOR (Table 1.16), and saline formations (Table 1.17) are summarised below. Figure 1.16 shows the median (P50) cumulative net CO_2 storage resources ($\boldsymbol{M_{CO2\ net}}$) across studied conventional oil and gas fields per basin. Figure 1.17 displays the P50-net storage resources in the examined oil and gas fields.

Table 1.15. Viet Nam: Estimated CO_2 Storage Resources in Hydrocarbon Fields

Basin	P50-Storage Available ($MtCO_2$)	P50-Storage Remaining ($MtCO_2$)	P50-Storage net ($MtCO_2$)	Number of Gas Fields	Number of Oil Fields
Cuu Long Basin	138.9	22.0	161.0	0	4
Nam Con Son Basin	96.6	45.8	142.4	4	1
Total	235.5	67.8	303.4	4	5

Source: GCCSI.

Table 1.16. Viet Nam: Estimated CO_2 Storage Resources in Oil Fields Assessed for CO_2 EOR-Storage

Basin	P50-Storage Available	P50-Storage Remaining	P50-Storage Net	Extra Oil Recovery (MMbbl) @RF5%	Extra Oil Recovery (MMbbl) - @RF30%
Cuu Long Basin	39.52	16.35	55.86	7.6	45.7

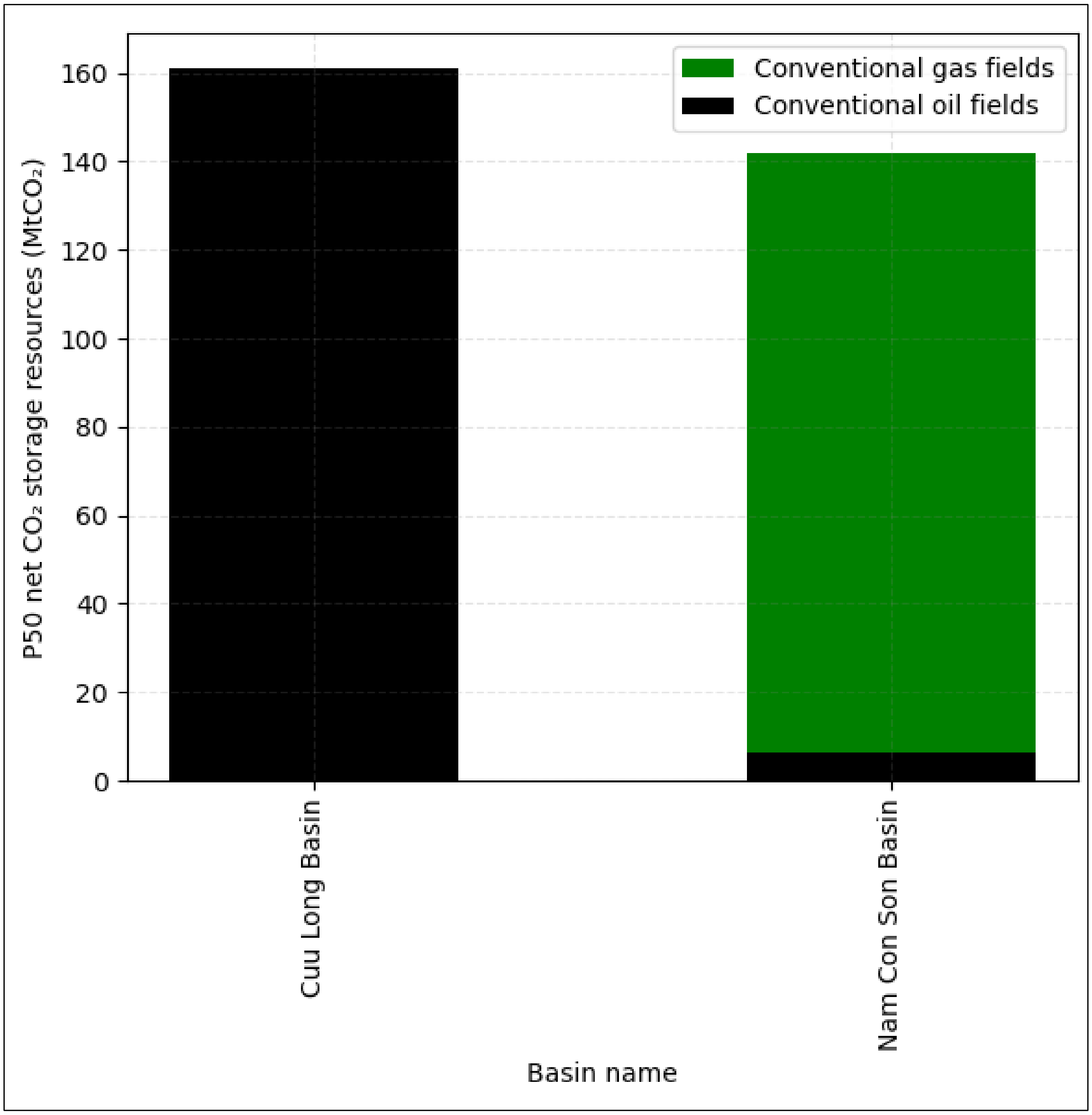
Source: GCCSI.

Table 1.17. Viet Nam: Estimated CO_2 Storage Resources in Saline Formations

Basin	Formation(s)	P90 ($GtCO_2$)	P50 ($GtCO_2$)	P10 ($GtCO_2$)
Cuu Long	Bach Ho	3	5	9

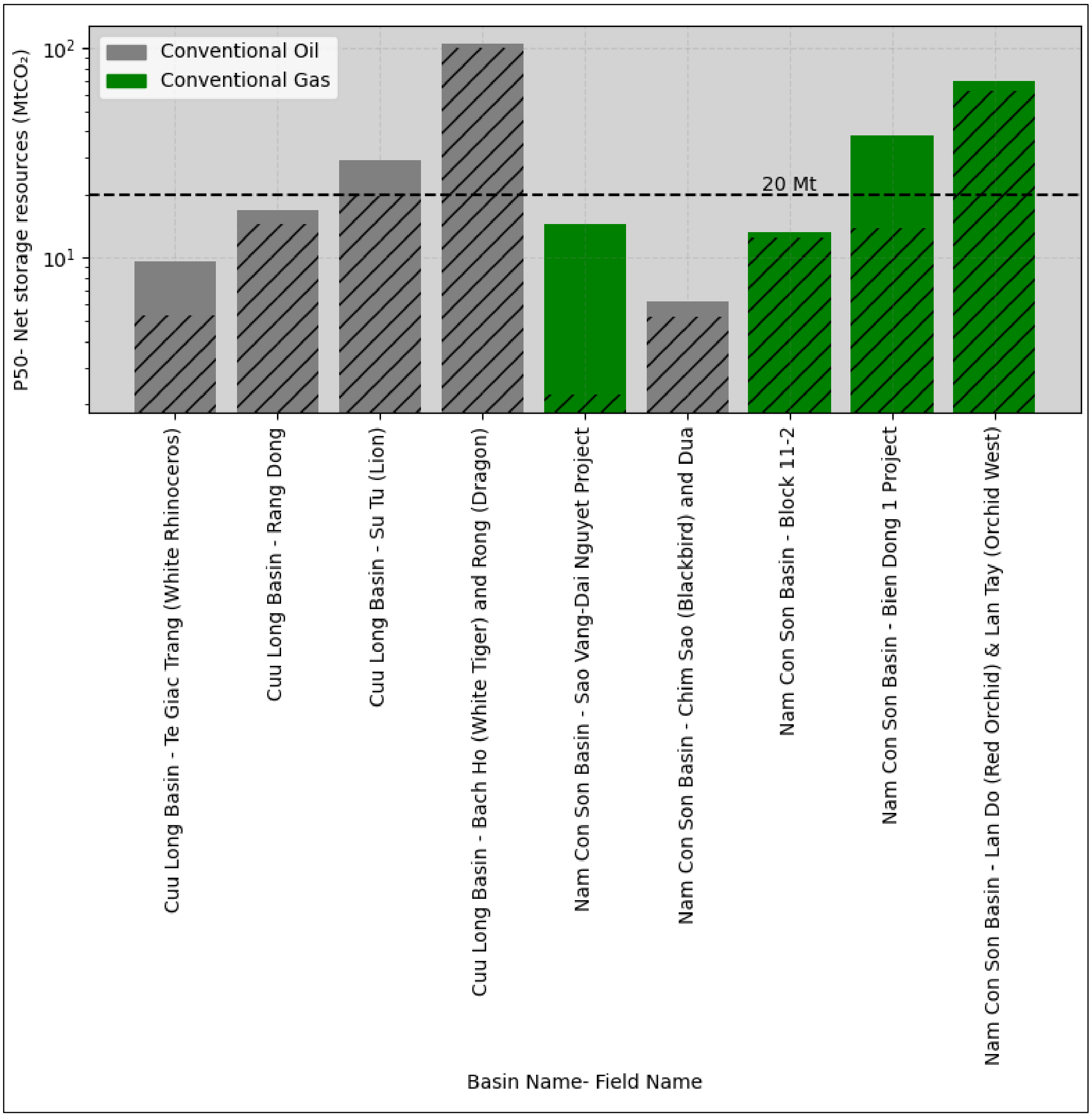
Source: GCCSI.

Figure 1.16. Cumulative P50 CO_2 Storage Resources in Studied Oil and Gas Fields per Basin Across Viet Nam



Source: GCCSI.

Figure 1.17. P50 Net CO_2 Storage Resources of Viet Nam's Studied Oil and Gas Fields



Note: the available CO_2 storage resources are shown as a texture on the bars.
Source: GCCSI.

1.3.6.2. Prospective Basins with Potential Clusters

Two significant clusters are present in Viet Nam, one surrounding Hanoi and the second in southwestern Viet Nam near Ho Chi Minh City (Figure 1.15). Viet Nam has two key storage basins (Nam Con Son and Cuu Long), but the only source-sink match is Ho Chi Minh City and the Cuu Long Basin.

1.3.6.2.1. Cuu Long Basin

The Cuu Long Basin is on the southern end of Viet Nam. The basin has an onshore and offshore component, although the offshore is the most prospective area inferred from the oil and gas fields.

Suitability

The basin is categorised as 'suitable' for CO_2 storage, according to the Institute's storage basin assessment tool. This assessment is based on:

- A moderate-sized (25,000-50000 km^2) basin with viable reservoir-seal pairs inferred from oil and gas fields.
- A single national published storage assessment with resource estimates. In addition, global or regional basin-scale storage assessments have been published with resource estimates of hydrocarbon fields and saline formations. Field/Formation or the data were not provided. Additional CO_2-EOR studies were also published, with only limited data provided.
- The extensive exploration and development of hydrocarbon fields mean the subsurface geology is well characterised.
- The legacy data associated with the mature hydrocarbon-producing basin reduces uncertainty in published resource estimates. Data associated with hydrocarbon exploration and production enables theoretical calculations of storage resources using real-world data.
- The mature hydrocarbon industry could provide access to legacy infrastructure such as pipelines, wells, platforms, etc., which could reduce timeframes to deployment and improve the economics of a CCS facility.
- Two pilot CO_2-EOR operations, White Tiger (Bach Ho) and Aurora (Rang Dong) were operational. A CCS Facility in a basin is a strong indicator of a viable storage resource and commercial opportunity for CCS, even as pilots.

Negative characteristics include:

- A convergent tectonic environment can increase the likelihood of major faulting, seismicity, and high geothermal gradient and pressure issues.
- The high CO_2 content of gas fields (many above 10% and some up to 80% (ADB, 2013) can compete for pore space with other industrial sources onshore.
- An offshore basin can increase an operation's costs and complexity.
- Viet Nam has no national regulatory regime.
- Viet Nam does not host a public system to access subsurface data.

The French Bureau des Recherches Géologiques et Minières (BRGM), in collaboration with Viet Namese counterpart KVN (Bureau des Recherches Géologiques et Minières, 2009), also identified the Cuu Long Basin as a priority basin in Viet Nam as part of a review of prospects for CO_2 storage of all basins across Viet Nam.

Storage Resources

The Cuu Long Basin is suitable due to the mature hydrocarbon industry and subsequent storage analysis associated with developing hydrocarbon fields. According to this analysis, this basin offers the highest CO_2 storage resources in hydrocarbon fields in Viet Nam, with P50-net CO_2 storage resources of around 161 $MtCO_2$ in four oil fields, most of which are available (139 $MtCO_2$) (Table 1.15).

The Bach Ho (White Tiger) and Rong (Dragon) offer the highest CO_2 storage resources amongst the studied fields. The field is estimated to hold 99 Mt of available CO_2 storage resources and 5.7 Mt of remaining CO_2 storage resources, for a total CO_2 storage resource base of around 105 Mt (Figure 1.17). The oil fields are approximately 60 m in water depth and were discovered in 1975 (Cuong & Warren, 2009). The fields comprise Mesozoic fractured 'basement' rocks (granites and volcanics) as well as overlying Oligocene fluvial-to-lacustrine clastic deposits of the Tra Tran Formation and Oligo/Miocene shallow marine-to-fluvial clastic deposits of the Bach Ho Formation – all of which serve as hydrocarbon reservoirs. Porosities in the Tra Tran Formation range from 9 to 15 % and from 12 to 25 % in the Bach Ho Formation (Cuong & Warren, 2009; Dien et al., 1997).

According to the analysis, three oil fields are suitable for CO_2 EOR storage; however, only one offers P50 Net storage resources higher than 20 $MtCO_2$, justifying averaged-sized, commercial-scale CCS facilities. Nonetheless, the cumulative extra oil that can be produced from these three fields in the basin ranges between 7.6 to 45.7 MMbbl, and the cumulative net CO_2 storage resources (P50) amount to around 56 $MtCO_2$ (Table 1.16).

The Bach Ho Formation is estimated to host 5 $GtCO_2$ (P50) storage resources and is the only studied saline formation in this analysis (table 1.17). The Bach Ho Formation comprises Late Oligocene to Early Miocene sandstones and mudstones in the Cuu Long Basin offshore Viet Nam. The sediments were deposited in shallow marine-to-fluvial environments, and sandstone thickness ranges from < 10 to 20 m. Bach Ho Formation's porosity ranges from 16 to 25 %, and permeability ranges from 1 to 5000 mD (Giao et al., 2016), making it a suitable target for CO_2 storage.

Beyond the Bach Ho Formation, the ADB (2013) assessed known hydrocarbon traps in six of eight basins of Viet Nam. The assessment indicates 300 $GtCO_2$ of storage basins across all storage basins and deep saline formations. The storage potential of fractured basement rock, which hosts some oil fields, is unknown. One detailed site scale analysis of the fractured basement rock using field data found the NV Gas Field could host between 7-99.5 $MtCO_2$

(Thanh et al., 2019).

The two clusters of emissions, north (Hanoi) and south (Ho Chi Minh), have very different prospects. The northern cluster would access the Song Hong Basin, which has almost no analysis of the storage potential. The Song Hong Basin is not a mature oil and gas province compared to other regional basins. For this reason, the basin is classified as 'possible' according to the Institute's storage basin assessment tool. Given that a significant portion of Viet Nam's emissions are proximal to this basin, extensive work is required on the basin's saline formation potential. Finally, the Nam Con Son Basin was omitted because it is not proximal to emissions sources.

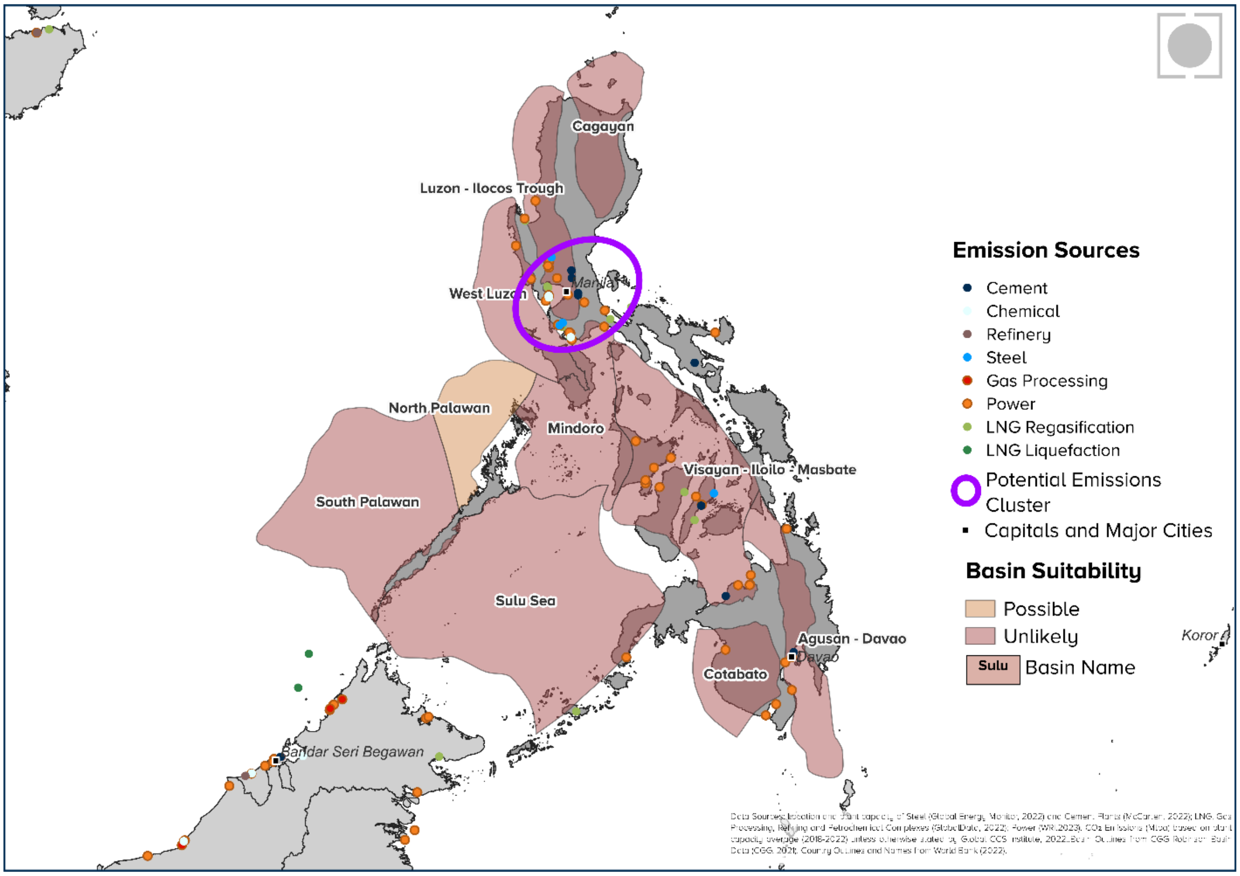
1.3.6.3. Summary of Storage Deployment Prospects, Barriers, and Issues

- Viet Nam lacks a modern, comprehensive national CO_2 storage resource atlas.
- The Cuu Long Basin requires a targeted characterisation study, focusing on saline formations and large depleted fields. Subsequently, the basin presents a moderate to long-term (<10 years) opportunity for CO_2 storage.
- The Song Hong Basin requires an extensive characterisation assessment, given a significant portion of Viet Nam's emissions are proximal to this basin.
- Viet Nam lacks a CCS-specific legal and regulatory framework and CCS-specific domestic policies or incentives.

1.3.7. Philippines

The storage potential of the Philippines is largely unknown and, therefore, has low prospects for hosting a large-scale CO_2 storage operation and CCS more generally in the near term. The Philippines' storage potential has been briefly reviewed as part of regional studies. No CCS facilities have been announced for the Philippines. One emission cluster in Luzon, near Manila, could form a CCS network (Figure 1.18).

Figure 1.18. Philippines Emission Clusters and Storage Basins



Source: GCCSI.

1.3.7.1. CO_2 Storage Resource Summary

Only one gas field passed the screening criteria used in this study (depth > 800 m and storage resources > 5 $MtCO_2$). Table 1.18 shows the storage resources of this field. No oil field could pass the criteria used for CO_2 EOR storage, mainly due to the small size of the fields. There was no data for saline formation resource estimates.

Table 1.18. Philippines: Estimated CO_2 Storage Resources in Hydrocarbon Fields

Basin	P50-Storage Available ($MtCO_2$)	P50-Storage Remaining ($MtCO_2$)	P50-Storage Net ($MtCO_2$)	Number of Gas Fields	Number of Oil Fields
North Palawan Basin	57.1	10.2	67.2	1	0

Source: GCCSI.

1.3.7.2. Prospective Basins with Potential Clusters

This analysis finds that the Philippines hosts only one basin with potential for CO_2 storage, albeit categorised as 'possible': the North Palawan Basin. The basin is entirely offshore, located off the island of Mindoro. The emissions cluster in Manila is a tenuous source-sink match as a ~500 km + pipeline from the Manila region to the North Palawan Basin would be required.

1.3.7.2.1. North Palawan Basin

The North Palawan Basin is classified as 'Possible' according to the Institute's storage basin assessment tool. The basin received this classification because it is hydrocarbon-producing, suggesting viable reservoirs and seals for CO_2 storage. However, overall, exploration and development in the basin are limited.

APEC (2005) and the ADB (2013) concluded that the prospects for storage in the Philippines were very low. Neither regional assessment provided extensive analysis or data to support their conclusions other than stating that the oil and gas fields in the North Palawan Basin did not present a significant opportunity based on field sizes. In addition, they noted the Luzon Basin, proximal to the emission sources of Manila, was of poor quality.

Storage Resources

The storage resource assessment of the Philippines is limited to a single gas field (Malampaya gas field) in the North Palawan Basin. The current study found that the Malampaya Gas Field had an estimated storage resource of 67.2 $MtCO_{2,}$ with 57.1 $MtCO_2$ available today (Table 1.18). The Malampaya gas field is situated at 850 water depth and was discovered in 1989. The field comprises Oligocene to Miocene carbonate build-ups (limestone) of the Nido Formation and sealed by mudstones of the overlying Pagasa Formation (Neuhaus, 2004). Porosity ranges from 5 to 30 %, and permeabilities range from 0.01 to 1,000 mD (Fournier & Borgomano, 2007).

The ADB (2013) also concluded that almost all hydrocarbon field resources were hosted in one unidentified field, 251 $MtCO_2$ (total of 307 $MtCO_2$).

The current analysis did not find sufficient data to complete a study of the saline formations of the Philippines. The ADB (2013) stated that Miocene to Pliocene shelfal sandstone has the best opportunity for further characterisation but noted that they were poor quality sandstones. According to the ADB, the storage resources in saline formations of the Luzon and Cagayan basins (both underlying Luzon Island) were estimated at around 32 Gt (ADB, 2013). Further analysis is required for the Sulu Sea, Cagayan, and Visayan basins if additional data can be identified or acquired.

Carbon Mineralisation

There are several notable mafic and ultramafic formations in the Philippines, each with unique characteristics and rock compositions. Some of these formations include:

- Zambales Ophiolite Complex: Located in Zambales Province, it is an extensive mafic and ultramafic rock formation. It comprises various rock units, including gabbros, basalts, and peridotites.
- Angat Ophiolites: Located in Luzon. It comprises layered and massive gabbros, diabase sheeted dikes, tonalites, and pillow basalts.
- Camarines Norte Ophiolite Complex: Located in Camarines Norte Province, it consists of harzburgites, gabbros, diabasic and basaltic dikes, and pillow lavas.
- Dinagat Ultramafic and Ophiolite Complex: Situated in the Dinagat Islands, this complex comprises ultramafic rocks such as dunites, peridotites, and serpentinites.
- Surigao Ophiolite Complex: Located in Surigao del Norte and Surigao del Sur provinces, this belt contains ultramafic rocks, including dunites, peridotites, and serpentinites.
- Leyte Ophiolite Complex: Located in Leyte province, this complex consists of ultramafic rocks such as peridotites and serpentinites.

The presence of ophiolites, dispersed across the Philippines in over 20 significant bodies, suggests a potential for carbon mineralisation in the country, provided they feature open, well-connected, and complex fracture networks.

A detailed evaluation is crucial to fully understand the potential and suitability of each formation for in-situ carbon mineralisation technology. Amongst the essential steps are precise quantification of their mineralogical composition, characterisation of their fracture networks and fluid flow properties, and comprehensive reactive transport modelling. With careful consideration of these factors, the Philippines can further explore the promising avenue of in-situ carbon mineralisation.

1.3.7.3. Summary of Storage Deployment Prospects, Barriers, and Issues

- The Philippines lacks a comprehensive national CO_2 storage resource atlas: the storage potential of onshore and offshore saline formations is unknown. A storage atlas mapping the formations is critical to advancing CO_2.
- A detailed evaluation is crucial to fully understand the feasibility and viability of the in-situ carbon mineralisation potential.
- The Philippines lacks a CCS-specific legal and regulatory framework and CCS-specific domestic policies or incentives.

1.3.8. Singapore

The geology of Singapore indicates there is no storage potential in that country. However, Singapore has significant emissions, primarily in the petrochemical and refining industries, requiring CCS for decarbonisation. Singapore, therefore, requires transboundary transport of CO_2.

The saline formations and/or hydrocarbon fields of Indonesia's Central Sumatra and North Sumatra basins are within 300 km of Singapore (Figure 1.5). However, Indonesia has significant domestic emissions in those regions that could result in competition for CO_2 storage resources. Alternatively, pipeline or shipping routes could export CO_2 to the Malay Basin in Malaysia. Competition for storage resources is less likely in the Malay Basin when compared to onshore Indonesian domestic CO_2 sources.

1.3.9. Cambodia, Lao PDR, and Myanmar

The storage potential of these nations is currently unknown as no analysis has been completed. Although they have comparatively minor emissions, CCS will eventually be required in each country.

The primary issue is a lack of CCS awareness and CO_2 storage expertise in these nations. They require the assistance of more advanced countries regionally (Thailand, Malaysia) and internationally.

It is recommended that these nations engage with the international storage community to progress CCS in each country. In addition, these nations currently do not have any CO_2 storage analysis, CCS-specific legal and regulatory frameworks or CCS-specific domestic policies or incentives.

1.4. Summary and Recommendations for Storage Development

This analysis confirms suitable storage basins across Southeast Asia with potentially gigatonnes of storage resources.

Overall

Most knowledge about the storage potential of the region's geology is derived from regional or global studies (ADB, 2013; CO2CRC, 2010; IEAGHG, 2009). Within those studies, resource estimates have focused on oil and gas fields but, in most cases, have not provided the data behind the estimates. Many of the basins in the region have not been reviewed for their storage potential. A limited number of basins have detailed site-specific studies published.

Despite over a decade of storage studies in Southeast Asia, a review of the countries above highlights three clear barriers to the development of CO_2 storage resources:

1) The storage resources of saline formations are largely unknown, and formations are uncharacterised.
2) Published storage resource estimates lack location, methodology, assumptions, limitations, or input data transparency. The raw data is unavailable in this current study due to copyright issues.
3) There is almost no access to subsurface data (such as geological data, well-log data, seismic reflection surveys, and core data).

These three barriers prevent the ongoing development of storage resources in Southeast Asia and restrict understanding of the applicability of CCS deployment in the region.

Each country is at a different stage of maturity in terms of CCS and storage development. A coordinated approach to storage resource development in Southeast Asia could accelerate the deployment of CCS in the region.

A series of public-private partnerships could sponsor the characterisation of storage basins in each nation. Each partnership would complete its assessment using a standardised approach to data collection, characterisation and resource calculations. The assessment results will be published in a public database of hydrocarbon fields and saline formations, showing the location, area extent, reservoir-seal properties, and resources, amongst other information critical for storage development.

As a public database, issues such as anti-trust or anti-competitive assertions can be avoided and enable industry to play a part. International experts and relevant experts in Indonesia, Malaysia, and Thailand could lead this programme to assist less advanced countries regarding CCS. The Southeast Asia CCS Accelerator (SEACA) initiative led by the Global CCS Institute laid the foundations of the above initiative by creating a storage working group in Jakarta in 2023.

The Jakarta SEACA Workshop was held physically on 20 and 21 November 2023 in Tangerang (near Jakarta), Indonesia and was co-organised by the Global CCS Institute, ASEAN Centre for Energy (ACE), and Asia Natural Gas and Energy Association (ANGEA). The Workshop was attended by representatives of six ASEAN Member States (Brunei Darussalam, Cambodia, Indonesia, Lao PDR, Malaysia, and Thailand) and Timor Leste. These representatives came from various sectors, including government, regulatory authorities, and state-owned companies. Additionally, invited participants from other government entities, industries, universities, consulting firms, etc., also participated.

The primary outcome of this meeting is to establish a Storage Working Group led by governments and supported by industry. The next steps of the Storage Working Group are now under consideration.

The specific recommendations for each county are detailed below. In addition, recommendations for each basin are described in Table 1.19. CCS policy is not discussed directly below. A general recommendation is to have supportive policies, such as carbon tax, that incentivise storage resource development, and CCS should be applied to every country.

Indonesia

Indonesia hosts multiple near-term opportunities to host significant CCS networks due to strong source-sink matching with sufficient onshore resources. With a regulatory framework in place, the development of storage resources relies on creating an environment for commercial success. Two key programmes can help create commercial success.

Firstly, producing a national storage atlas with public and open data (well, seismic, etc.) can bolster commercial success. An atlas identifies where storage resources are located and how much can be stored. An atlas also identifies data gaps and major risks. An atlas will also enable a comprehensive mapping and characterisation of saline formations, which has not been done in Indonesia.

Mapping these storage resources opens up a broader understanding of the overall CCS potential of Indonesia, rather than that knowledge (and data) being limited to only the oil and gas industry as it stands today. In addition, new storage operators could rapidly progress initial screening analysis by using the outcomes and data of the atlas. Finally, an atlas can enable the regulator to release storage leases in areas with the highest chance of uptake.

Based on the findings of the atlas, a government-led de-risking of storage resources through pre-competitive data acquisition can remove the initial cost barrier to storage exploration. The key focus should be areas with limited hydrocarbon exploration and production but likely have suitable saline formations. The acquisition could focus on filling data gaps, such as acquiring seismic over areas with no or limited seismic lines. The primary focus should be on those emission-intensive regions where data is limited.

For example, the Australian Government funded the national geological survey to complete several pre-competitive data acquisition programmes to support storage development. A CCS project has been announced in each area where data was acquired. (https://www.ga.gov.au/scientific-topics/energy/resources/carbon-capture-and-storage-ccs/geological-storage-studies).

Malaysia

The above strategies, a comprehensive atlas and a pre-competitive work programme for Indonesia, apply to Malaysia. Malaysia has multiple opportunities to host significant CCS networks with multiple emission clusters adjacent to suitable storage basins on the east coast of the Malay Peninsula and Sarawak. In the near term, the development would be restricted to the Sarawak region, which has a regulatory framework. Therefore, having national regulatory frameworks across Malaysia to support the exploration and development of storage is a priority.

The industrial emissions surrounding Kuala Lumpur present an interesting scenario. The closest storage options are in Indonesia's onshore basins. In contrast, the nearest known domestic storage options are in the Malay Basin, approximately 500 km away (direct), requiring shipping or a pipeline across the Malay Peninsula. The storage potential of the Strait of Malacca is currently unknown because there is no national atlas.

Finally, the 100 GtCO_2+ storage resources in Malay, Sabah, and Sarawak basins offshore Malaysian waters enable the opportunity to receive international CO_2 through shipping.

Thailand

Thailand does not have CCS-specific regulatory frameworks. A national regulatory framework to support the exploration and development of storage is a priority. Regarding storage development programmes, Thailand has the exact requirements as Malaysia and Indonesia - a national atlas mapping and characterising saline formations and hydrocarbon fields. This atlas can then be followed by a government-led pre-competitive data acquisition programme to de-risk sites and fill data gaps.

Given the storage resources are restricted to the offshore Gulf of Thailand, ~ 500 km from the major emission clusters around central and eastern Thailand, the exploration and appraisal of onshore basins is critical. Accessing onshore storage resources would significantly reduce transport and storage costs.

Other Southeast Asia Nations

Brunei, the Philippines and Viet Nam do not have regulatory frameworks, so that should be a priority for the government. Each country requires a national atlas of storage resources to identify potential storage sites within saline formations and to identify risks and barriers to deployment.

Brunei could potentially have the most rapid movement once regulations are in place. The country hosts a suitable basin for CO_2 storage and large, near-depleted oil and gas fields that could be converted to storage sites. Moreover, the limited domestic emissions compared to the overall storage resource of the Sabah-Baram Delta Basin means international import of CO_2 could be commercially viable.

In Viet Nam, the storage resources of the northern Song Hong Basin are unknown. This region would host the largest CCS Network in Viet Nam due to emissions clusters in and around

Hanoi. In southern Viet Nam, the emissions clusters around Ho Chi Minh City could access the resources of the offshore Cuu Long Basin. The storage potential of the saline formations of the offshore Cuu Long Basin is unknown and must be mapped and characterised.

The Philippines requires a fundamental analysis of its storage resources, focussing on the storage potential proximal to its emissions centres around Manila. This should include mineral carbonation evaluation.

Lao PDR, Cambodia, and Myanmar

Lao PDR, Cambodia, and Myanmar require a fundamental analysis of their storage resources. An international or fellow ASEAN nation should support this work to rapidly bring these three nations up to speed in understanding their CO_2 storage potential.

A summary of each basin and the required work programme is detailed in Table 1.19.

Table 1.19. Summary of the Storage Potential and Future Work Programmes of Southeast Asia Region

Country	Basin	Location	Basin Suitability	Emission Cluster Identified	Storage Resource Estimate Completed		Requirements for Accelerated Deployment
					Oil and Gas	Saline Formations	
Viet Nam	Song Hong	Offshore	🟠	P	X	X	1. Basic analysis of storage potential and resource calculations 2. Regulations to enable the exploration and storage of CO_2 storage
	Cuu Long	Offshore	🟢	P	P	P	1. Characterisation of saline formations with resource calculations 2. Detailed hydrocarbon field suitability and resource assessment 3. Infrastructure analysis to review potential for re-use 4. Regulations to enable the exploration and
	Nam Con	Offshore	🟢	X	P	X	1. Characterisation of saline formations with resource calculations 2. Detailed hydrocarbon field suitability and resource assessment 3. Infrastructure analysis to review potential for re-use 4. Regulations to enable the exploration and storage of CO_2 storage

Philippines	North Palawan	Offshore	●	X	P	X	1. Characterisation of saline formations with resource calculations 2. Detailed hydrocarbon field suitability and resource assessment 3. Infrastructure analysis to review potential for re-use 4. Regulations to enable the exploration and
	Luzon	Onshore	●	P	X	X	1. Basic analysis of storage potential and resource calculations 2. Basic mineral carbonation potential 3. Regulations to enable the exploration and storage of CO_2 storage
Thailand	Pattani	Offshore	●	P	P	P	1. Characterisation of saline formations with resource calculations 2. Detailed hydrocarbon field suitability and resource assessment 3. Regulations to enable the exploration and storage of CO_2 storage
Malaysia/ Thailand	Malay	Offshore	●	P	P	P	1. Characterisation of saline formations with resource calculations 2. Detailed hydrocarbon field suitability and resource assessment 3. Infrastructure analysis to review potential for re-use 4. Brunei to regulations to enable the exploration and storage of CO_2

Malaysia	Sarawak	Offshore	●	P	P	P	1. Characterisation of saline formations with resource calculations 2. Detailed hydrocarbon field suitability and resource assessment 3. Infrastructure analysis to review potential for re-use
Malaysia	Sabah-Baram	Offshore	●	P	P	P	1. Characterisation of saline formations with resource calculations 2. Detailed hydrocarbon field suitability and resource assessment 3. Infrastructure analysis to review potential for re-use
Brunei	Sabah-Baram	Offshore	●	P	P	P	1. Characterisation of saline formations and hydrocarbon fields with resource calculations 2. Regulations to enable exploration and storage of CO_2 storage
Myanmar	Central Myanmar	Onshore	●	P	X	X	• Basic analysis of storage potential and resource calculations
Cambodia	Panjang	Offshore	●	X	X	X	• Basic analysis of storage potential and resource calculations
Laos	Greater Korat	Onshore	●	X	X	X	• Basic analysis of storage potential and resource calculations
Indonesia	Central Sumatra	Onshore	●	P	P	P	• Characterisation of saline formations with resource calculations

	South Sumatra	Onshore	●	P	P	X	1. Characterisation of saline formations with resource calculations 2. Detailed hydrocarbon field suitability and resource assessment 3. Infrastructure analysis to review potential for re-use
	Northwest Java	Onshore	●	P	P	X	1. Characterisation of saline formations with resource calculations 2. Detailed hydrocarbon field suitability and resource assessment 3. Infrastructure analysis to review potential for
	Northeast Java	On/Offshore	●	P	P	X	1. Characterisation of saline formations with resource calculations 2. Detailed hydrocarbon field suitability and resource assessment 3. Infrastructure analysis to review potential for
	East Java	Offshore	●	P	P	P	1. Characterisation of saline formations with resource calculations 2. Detailed hydrocarbon field suitability and resource assessment 3. Infrastructure analysis to review potential for
	Kutei	Offshore	●	P	P	P	• Detailed hydrocarbon field suitability and resource assessment • Infrastructure analysis to review potential for
SINGAPORE	No storage		●	P	X	X	• Engage adjoining regions to support their storage development.
LEGEND	**Basin Suitability**		● Highly Suitable		● Suitable		● Possible ● Unlikely

Source: GCCSI.