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Estimating Basin-Scale CO_2 Storage in Indonesia

Prepared by
Center for Technology Services
National Research and Innovation Agency (BRIN)

In Collaboration with
Testing Center for Oil and Gas LEMIGAS, and
Center for Geological Survey – Geological Agency,
Ministry of Energy and Mineral Resources, Indonesia

With Support of
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Economic Research Institute for ASEAN and East Asia

ASIA CCUS NETWORK

Estimating Basin-Scale CO_2 Storage in Indonesia

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Preface

ASEAN member states (AMSs) target achieving carbon neutrality in 2050–2070. On the other hand, they will need to continue their remarkable economic growth until 2050 to catch up with countries of the Organisation for Economic Co-operation and Development. Thus, energy prices should be affordable for them using fossil fuels, which are available, accessible, and affordable. Under this condition, carbon capture and storage (CCS) will be an option for AMSs to maintain affordable energy prices and achieve carbon neutrality. Regarding CCS, carbon dioxide (CO_2) storage capacity should be crucial. In this regard, the Economic Research Institute for ASEAN and East Asia (ERIA) contracted the National Research and Innovation Agency (BRIN) for a study titled 'Estimation of Basin-Scale CO_2 Storage in Indonesia', a famous country with CO_2 storage potential in the ASEAN region.

This report represents collaboration amongst experts and stakeholders to provide a comprehensive assessment of the CO_2 storage potential in the sedimentary basins of Indonesia. It ranks 128 sedimentary basins in terms of CO_2 storage suitability and CO_2 storage assessment, with an estimation level ranging from basin-scale for saline aquifers to field-scale for hydrocarbon reservoirs; classifies the quantitative estimates of CO_2 storage in terms of data availability; and integrates the results into a tool based on Geographic Information System (GIS).

As the Secretariat of the Asia CCUS Network, ERIA believes that this report can provide insights into the development and deployment of CCUS as a pivotal climate mitigation technology in Indonesia and the Southeast Asia region.

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Acknowledgement

This report describes the study on basin-scale CO_2 storage assessment in Indonesia sponsored by the Economic Research Institute for ASEAN and East Asia (ERIA) and Asia CCUS Network (ACN). The report is prepared by a joint team of experts from the Center for Technology Service–National Research and Innovation Agency (Pusyantek–BRIN), the Testing Center for Oil and Gas LEMIGAS–Directorate General of Oil and Gas, and the Center for Geological Survey (PSG)–Geological Agency, Ministry of Energy and Mineral Resources of Indonesia.

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List of Abbreviations

CCS	carbon capture and storage
CCUS	carbon capture, utilisation, and storage
CO_2	carbon dioxide
GHG	greenhouse gas
GIS	Geographic Information System
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
LNG	liquefied natural gas
NZE	net-zero emission
OGIP	original gas-in-place
OOIP	original oil-in-place
SRMS	storage resources management system
US	United States

Executive Summary

Decarbonising the global energy system will require a fundamental transformation of producing, transporting, and consuming energy. The International Energy Agency's Net Zero by 2050 Roadmap (IEA, 2021) for the global energy sector highlights the scale of the challenge and the need for immediate and massive deployment of all available low-carbon energy technologies. One potential technology reduction option is carbon capture, utilisation, and storage (CCUS). The analysis underscores the critical role of CCUS technologies in putting the world on a path to net-zero emissions (NZE), contributing more than 10% of cumulative emissions reductions globally by 2050.

There are worldwide plans for more CO_2 capture volumes over the next 5 years, from around 40 Mt CO_2 per year to 1.6 Gt CO_2 in 2030, and a rapid expansion to 7.6 Gt CO_2 over the following 25 years. In Southeast Asia, CCUS would build from a limited base today to 200 Mt or more in 2050. Around 95% of the total CO_2 captured in 2050 is stored in permanent geological storage. Identifying and determining CO_2 storage resources are critical issues in taking CCUS forward. A hub approach through regional cooperation, shared infrastructure, and the development of large, shared CO_2 storage sites can support faster deployment of CCUS in Southeast Asia.

Indonesia could play an essential role in CCUS deployment in the region because of the availability of vast sedimentary basins that contain geological media suitable for CO_2 storage, such as oil and gas reservoirs and deep saline aquifers. A total of 128 sedimentary basins exist across the Indonesian archipelago. Twenty contain oil and gas reservoirs proven to store significant quantities of buoyant fluids such as oil, gas, and CO2. The rest are 27 discovery basins not yet in production, 12 prospective basins with seismic and well data available, and 69 unexplored basins.

Oil and gas reservoirs are prime candidates for CO_2 storage because they have been proven to store significant quantities of buoyant fluids such as oil, gas, and CO_2. They have been extensively studied and have significant amounts of geological and engineering data available for detailed site characterisation. Many studies have identified saline aquifers as one of the best potential options for large-volume geological storage of CO_2 and extensive spatial distribution in most sedimentary basins, although commonly less understood and typically include significant uncertainty due to the lack of subsurface data.

Several studies of CO_2 storage resources have been conducted in selected sedimentary basins of Indonesia. The storage resources were estimated up to 69 Gt in the selected saline aquifers in North West Java, East Java, North Sumatra, Central Sumatra, and South Sumatra basins. The CO_2 storage resources within oil and gas reservoirs assessed were estimated at 2.5 Gt for an optimistic level in 12 hydrocarbon fields. The results appear small, suggesting that all available pore volume across the sedimentary basins of Indonesia may not have been evaluated.

This study is more advanced than others as it ranks 128 sedimentary basins in terms of CO_2 storage suitability, CO_2 storage assessment with level of estimation ranging from basin-scale for saline aquifers to field-scale for hydrocarbon reservoirs in selected sedimentary basins; classifies the quantitative estimates of CO_2 storage in terms of data availability; and integrates the results into a tool based on Geographic Information System (GIS).

A sedimentary basin database has been established to develop a screening and ranking system for CO_2 storage suitability and estimate the CO_2 storage resources in deep saline aquifers and hydrocarbon fields. Data is collected from multiple sources databases including but not limited to reserves and PVT databases managed by LEMIGAS, sedimentary basin database from Geological Agency (2009, 2022), Indonesia Oil and Gas Field Atlas and Geothermal Gradient Map of Indonesia issued by the Indonesian Petroleum Association (IPA), and LEMIGAS internal reports.

Synthesis of eliminatory and selection screening processes have been applied to evaluate the overall suitability of Indonesia's sedimentary basins for CO_2 storage. The elimination process using the minimum depth of 800 m ruled out 32 sedimentary basins. These 32 basins are then excluded from the selection process for quantifying CO_2 storage suitability and ranking process. The 16 screening criteria reflecting the uniqueness of Indonesian geology are defined and grouped into four categories related to data availability, storage potential, security, and environment to determine their relative importance among the criteria. A pairwise comparison approach is applied to the weight of each criterion.

The results of this study show that sedimentary basins with a top rank in terms of their suitability for CO_2 storage dominated by producing basins lead to high weighting factor. They also attributed it to large basin size, located onshore to shallow water depth, in relatively stable geological activity, and having a low geothermal gradient compared to others.

CO_2 storage resources in deep saline aquifers are estimated based on the volumetric method and limited to depths between 800 and 2,500 m. A new approach has been introduced by adding a trap geometric multiplier into the volumetric equation to represent the effective average of the closure area. Indonesia's CO_2 storage resources in deep saline aquifers are estimated to be 680.57 Gt distributed across 21 sedimentary basins and classified as prospective storage resources (3U). Kutai Basin shows significant CO_2 storage resources of 152.95 Gt.

CO_2 storage resources in oil and gas fields are defined on a volumetric basis and estimated based on reserves databases that report the original gas-in-place (OGIP), original oil-in-place (OOIP) and estimated ultimate recovery factor (RFEUR) for each field under development or approved for development. The number of fields assessed is 1,068, comprising 728 oil and 340 gas fields. Indonesia's CO_2 storage resources in hydrocarbon fields are estimated to be 1.30 Gt in 728 oil fields and 8.84 Gt in 340 gas fields. Gas fields have significant CO_2 storage resources compared to oil fields because of their large size and recovery factor of 80%–90%. These storage resources are classified as contingent storage resources, assessed and categorised as C1 according to the SPE Storage Resources Management System (SPE SRMS), which is equivalent to the proved category. The total C2 and C3 categories, which are equivalent to probable and possible categories, in all oil and gas reservoirs are 1.22 and 1.20 Gt, respectively.

A summary of CO_2 storage resources in both deep saline aquifers and hydrocarbon fields based on the framework of the SPE SRMS is presented in Table S.1. Given the significant potential of CO_2 storage, Indonesia is well suited to be part of the regional CCUS hub.

Table S.1. Summary of Indonesia's CO_2 Storage Resources

Reservoir	Total Storage Resources, Gt									
	Discovery							Undiscovery		
	Stored	Capacity			Contingent			Prospective		
		1P	2P	3P	1C	2C	3C	1U	2U	3U
Oil					**1.30**	**1.36**	**1.47**			
Gas		**0.03**	**0.03**	**0.03**	**8.81**	**9.97**	**11.07**			
Saline										**680.57**

Source: Authors.

A GIS-based tool for viewing CO_2 storage resources across the Indonesia sedimentary basins has been developed. The tool allows the display dispersing of the CO_2 storage resources by basins and distinguishes the category of contingent CO_2 storage resources in hydrocarbon fields.

This report should be of interest to a broad audience interested in reducing CO_2 emissions, such as policymakers, government agencies, project developers, academicians, and civil society and environmental non-governmental organisations, to enable them to assess the role of CCUS as a major carbon management strategy in the energy sector to stay on a pathway compatible with the target of the Paris Agreement. The report provided technical data supporting policy recommendations to advance CCUS development in Indonesia and Southeast Asia.

Chapter 1
Introduction

1. Context

As the human population and industrial activity grow, the demand for energy access continuously rises, with fossil fuels remaining the most dominating source. The significant environmental problem associated with fossil fuel use is the emission of greenhouse gases (GHGs). The energy sector accounted for around three-quarters of GHG emissions in recent years and holds the key to averting the worse effects of global warming and problems related to climate change. In 2022, global energy-related CO_2 emissions as the primary GHG are sharply rebounding as economics recover from last year's pandemic-induced shock, reaching a new all-time high of 36.8 Gt (IEA, 2022). Taking urgent action to cut global CO_2 emission and mitigate the devastating impacts of climate change is therefore an imperative to save lives and livelihood.

The International Energy Agency (IEA) has mapped out how the global energy sector can reach net-zero emission (NZE) by 2050 and stay on the pathway to limit the long-term increase in average global temperature to 1.5^{o}C scenarios as assessed by the Intergovernmental Panel on Climate Change (IPCC) (IEA, 2021a). The map is produced to show what is needed across the main sectors by various actors and by when to achieve net-zero energy-related CO_2 emissions by 2050. This involves all countries participating in efforts to meet the net-zero goal, working together effectively and in a mutually beneficial way, recognising the various stages of economic development of countries and regions, and the importance of ensuring a well-just transition.

Decarbonising the global energy system will require a fundamental transformation of producing, transporting, and consuming energy. The IEA Net Zero by 2050 Roadmap for the global energy sector highlights the scale of the challenge and the need for immediate and massive deployment of all available low-carbon energy technologies. One potential technology reduction option is called carbon capture, utilisation, and storage (CCUS) (Eiken et al., 2011; Alcalde et al., 2018; Anthonsen and Christensen, 2021). The analysis underscores the critical role of CCUS technologies in putting the world on a path to NZE, contributing more than 10% of cumulative emissions reductions globally by 2050.

CCUS refers to a suite of technologies involving the capture of CO_2 from large point sources or directly from the atmosphere, then compressed and transported by pipeline, ship, or truck to be used in a range of applications or injected into deep geological formations that trap the CO_2 for permanent storage. The extent to which CO_2 emissions are reduced in net terms depends on how much CO_2 is captured from the point source and whether and how the CO_2 is used. The role of CCUS spans all parts of the global energy system, including heavy industry, low-carbon hydrogen production, power generation, carbon removal from the atmosphere through biomass energy with CCS and direct air CCS, and as a source of CO_2 for synthetic fuels.

After years of slow progress, strengthened climate goals and commitments from governments and industry are building new momentum behind CCUS. Worldwide plans for more CO_2 capture volumes over the next 5 years, from the current level of around 40 Mt CO_2 per year to 1.6 Gt CO_2 in 2030, and a rapid expansion to 7.6 Gt CO_2 over the following 25 years. Almost 50% of the CO_2 captured in 2050 is from fossil fuel combustion, 20% is from industrial processes, and around 30% is from bioenergy use with CO_2 capture and direct air capture. About 95% of total CO_2 captured in 2050 is stored in permanent geological storage, and 5% is used to provide synthetic fuels (IEA, 2021a).

Interest in CCUS is also expanding in Southeast Asia in line with international trends. CCUS will build from a limited base in the region today to 200 million tonnes (Mt) or more of CO_2 capture by 2050 (IEA, 2021b). Almost 90% of Southeast Asia's energy demand growth has been met by fossil fuels and the region is home to significant coal and liquefied natural gas (LNG) exporters. While the opportunity for CCUS goes beyond fossil fuel applications, the technology can be an important pillar for helping the region transition from its current energy mix to one that is aligned with future climate goals.

Regional cooperation and shared infrastructure can support faster deployment of CCUS in Southeast Asia. The establishment of the Asia CCUS Network in June 2021 is a significant milestone and opportunity to advance CCUS in the region. A hub approach will support the economies of scale and kick-start CCUS deployment in the region. The development of large, shared CO_2 storage sites that multiple facilities and countries can access could support CCUS investment in locations where storage capacity is limited or where its development faces delays. Such an approach could incorporate offshore CO_2 storage CO_2 shipping, providing additional flexibility and contingency in the CCUS value chain where several storage facilities are available.

Indonesia could lead CCUS deployment in the region and is already exploring opportunities to advance CCUS technology across a broad range of sectors (power, industry, upstream oil and gas) and fuels (coal, biomass, oil). Indonesia has also undertaken detailed studies on CCUS potential in the form of CO_2-enhanced oil recovery (CO_2-EOR) (Usman, 2016; Usman, Iskandar, and Sismartono, 2019; Usman et al., 2014). Indonesia, being at the crossroads of the Asian–Australian continents and the Pacific and Indian Oceans (Djumala, Bainus, and Sumadinata, 2022), is well suited to be part of the regional CCUS hub. A vital step to facilitate CCUS development in Indonesia is by releasing CCS and CCUS regulation on upstream oil and gas business activities. The provisions are in Energy Minister Regulation Number 2/2023, issued on 2 March 2.

One of the first steps to evaluate regional CCUS options is to identify and estimate the storage potential of suitable geological formations. Storage sites will likely be broadly distributed in many sedimentary basins in the same region as many emission sources will be adequate to store a significant proportion of those emissions into the future. Indonesia is home to the abundant sedimentary basins among countries in Southeast Asia.

About 128 tertiary sedimentary basins, spread out from Sumatra in the west to Papua in the east, are identified. So far, only 47 basins have been explored and drilled for petroleum, and 20 are now producing oil and gas.

CO_2 can be geologically stored in various geological settings in sedimentary basins: oil and gas reservoirs, deep saline aquifers, and coal beds (Bachu, 2003; IPCC, 2005; CSLF, 2007; CO2CRC, 2008). Oil reservoirs possess, at depletion, smaller storage capacity than gas reservoirs or deep saline aquifers. However, if they are suitable for CO_2 EOR, their storage resources will increase, and the storage cost will decrease by producing additional oil. Gas reservoirs have significant CO_2 storage resources because of their large size, and their recovery factor of between 80% and 90% is very large. Saline formations are considered the best potential options for CO_2 geological storage due to their large storage capacities and extensive spatial distribution in most sedimentary basins. CO_2 storage in coal seams is by adsorption instead of storage in rock pore space of hydrocarbon/saline formations. Identifying and developing CO_2 storage resources across the Indonesian territory are crucial to unlocking the CCUS potential in the region.

2. Previous Studies

Several studies of CO_2 storage have been performed in selected sedimentary basins of Indonesia. An initial study by the Research and Development Center for Oil and Gas Technology (LEMIGAS), supported by the Asian Development Bank's CCS trust fund in 2013 ADB, 2013), assessed storage potential in the South Sumatra basin. The South Sumatra basin was divided into four subbasins: South Palembang, Central Palembang, North Palembang, and Jambi. Both sandstone- and carbonate-hosted saline aquifers were evaluated. The sandstone reservoirs are mainly found in Talang Akar and Lahat formations, while the carbonate reservoirs are in Batu Raja and Lower Telisa formations. The total prospective storage resources were estimated at 7.6 gigatons of CO_2 (Gt CO_2) in saline aquifers below 1,000 meters overburden, consisting of 7.4 Gt CO_2 in porous sandstone and 0.2 Gt CO_2 in porous carbonate rock. The contingent storage resource was estimated at 92 million tonnes of CO_2 (Mt CO_2) in 98 oil fields examined in this study, representing 59% of the total original oil-in-place (OOIP) in the South Sumatra basin and 831 Mt CO_2 in 35 gas fields assessed, accounted for 47% of the total original gas in-place (OGIP) in South Sumatra. The storage estimates for oil and gas reservoirs in the South Sumatra basin presented in this report are only partial, as sufficient data were unavailable for all the reservoirs at the time of the study. Because oil and gas reservoirs were reported at the field scale and saline formations were reported at the basin level, a cross-comparison of estimates may not be useful.

LEMIGAS, State Electricity Company (PLN), and the World Bank conducted a study in 2015 to update storage resources in the South Sumatra basin and expanded to include the West Java basin. This study aimed to define and evaluate the conditions under which coal-based generation could be deemed CCS-ready. The geological formations of the South Sumatra basin considered in this study consist of sandstone Talang Akar, limestone Batu Raja, and a small portion of clastic Lemat. They lie in depth between 1,000 m to 2,500 m. The contingent storage resources amounted to 43 Mt CO_2 in 127 oil fields, including additional pore volume that will be made for storage at reservoir depletion by EOR and 537 Mt CO_2 in 45 gas fields. The prospective storage resource was estimated at 3.7 Gt CO_2 P50 in saline aquifers. In the North West Java basin, the geological formations are represented by Late Oligocene Talang Akar siliclastics, Lower Miocene Batu Raja carbonate, and Early Miocene Upper Cibulakan sandstone. A total of 51 gas field data collected comprise 22 onshore and 29 offshore. The total contingent storage resources of both were approximately 395 Mt CO_2, while the prospective storage resource of 4,9 Gt CO_2 was identified in saline aquifers.

Li et al. (2022) studied the CO_2 storage sites within oil- and gas-depleted reservoirs and saline aquifers in selected basins of Indonesia as part of the CCS feasibility study in Southeast Asia. Indonesia's sedimentary basins included in this study were the Kutei, South Sumatra, and North Sumatra basins. Kutei provided 1,908 Mt CO_2 at a conservative level of 2,526 Mt CO_2 for an optimistic level in 12 hydrocarbon fields and 32–67 Gt CO_2 in saline aquifers. Storage resources were estimated at 486–676 Mt CO2 in 15 hydrocarbon fields and 13–23 Gt CO_2 in saline aquifers within the South Sumatra basin. Storage resources identified within the North Sumatra basin were 964–1,155 Mt CO_2 from 8 hydrocarbon fields and 5–8 Gt CO2 from saline aquifers.

Ryoko Setoguchi (2023) presented the CO_2 storage estimation in saline aquifers in five production basins in Indonesia: North West Java, East Java, North Sumatra, Central Sumatra, and South Sumatra basins. Assessed formations in North West and East Java basins were Parigi, Massive/Main, Batu Raja, and Talang Akar. A significant CO_2 storage resource of around 69 Gt was identified in all formations. Targeted formations within the basins situated in Sumatra were Upper Benio, Sihapas and Telisa, Batu Raja, and Pematang. They have a total CO_2 storage resource of 56 Gt. All estimations represented mid-cases.

The LEMIGAS Center of Excellence have conducted site-specific CO_2 storage assessments for CCS and CCUS (Usman, Iskandar, Sugihardjo, and Lastiadi (2014); Usman, Iskandar, Sismartono (2019). Since 2012, detailed studies have been undertaken to assess the feasibility of the CCUS pilot project at the Gundih gas field in Central Java. The Gundih CCUS Project, which has a planned capture capacity of 0.3 Mt CO_2 per year from natural gas processing, will be geologically stored in conjunction with enhanced gas recovery. A more accurate simulation model is applied in this study. An estimated total of 3 Mt CO_2 will be stored in the 10-year project. This study was conducted in collaboration with PT Pertamina, J-POWER, and Japan NUS Co. and supported by the Japanese government.

A notable study, led by LEMIGAS, to evaluate the feasibility of CCUS in the form of CO_2 EOR at the Sukowati oil field in East Java concluded that there is a potential to store 14.2 Mt CO_2 in 25 years. The studies started in 2018, supported by the Asian Development Bank through the CCS Trust Fund. It continues to the present under collaboration PT Pertamina, Japan Petroleum Exploration Co., Ltd. (JAPEX), and supported by the Japanese government with the anticipated application of the Joint Crediting Mechanism. Pertamina's proposed CO_2-EOR project in the Sukowati involves an initial pilot intended to be scaled up to a full-field application years later. The CO_2 produced during oil and gas production from the Sukowati field is designed to be reused for pilot injection. The full-field CO_2-EOR project would involve the capture of CO_2 from the Jambaran Tiung Biru natural gas field. The essential factors of CCUS were also studied, including CO_2 pipeline design, wellbore integrity, geomechanics for cap rock integrity, and outreach strategy with a more favourable local context.

Along with the CCUS Sukowati study in 2019, CCUS potential with CO_2 EOR application for the Limau-Niru oil field in South Sumatra was also undertaken by LEMIGAS, PT Pertamina, and JAPEX. The study included more accurate reservoir simulation with a sector model for co-optimisation of oil recovery and CO_2 storage, a detailed investigation of wellbore integrity, developed a site-specific monitoring program, and made an inventory of CO_2 sources for Limau-Niru CCUS. The result showed that more CO_2 injected mixed with the oil is produced back, leading to a total CO_2 of 139 kilotons (Kt) that could be stored for 10 years of simulation period.

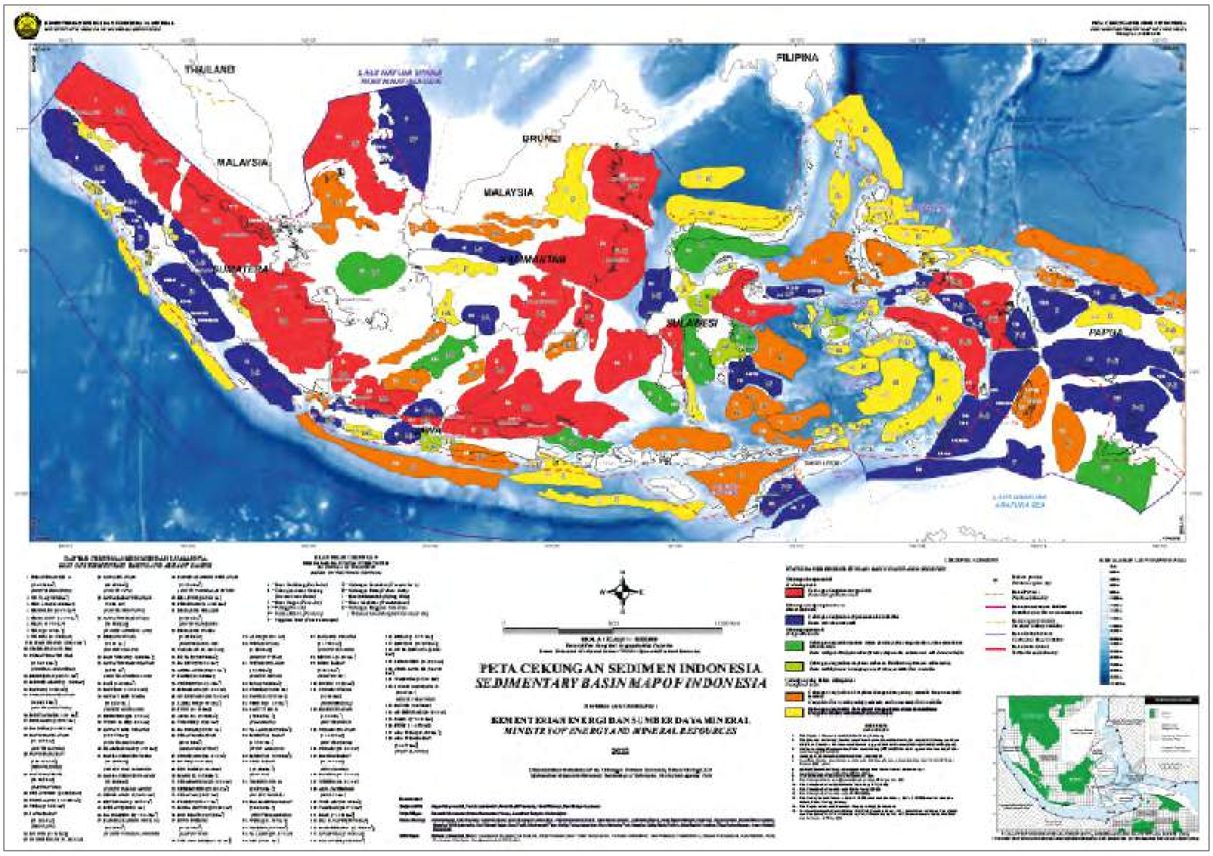
Several CCUS studies are underway as part of gas field development projects in Indonesia. One of them is Tangguh LNG EGR/CCUS project, which works by separating the reservoir CO_2 from produced gas and reinjecting it back to the Vorwata gas field for sequestration and enhanced gas recovery. The total emissions reduction is up to 25 Mt of CO_2 equivalent by 2035 while up to 300 billion standard cubic foot of natural gas is produced as additional LNG cargoes for the domestic and international markets. This would make Tangguh one of the world's lowest carbon-intensity LNG plants.

The above studies have in many ways been steppingstones to one another. Still, there are significant differences between the studies concerning several basins and hydrocarbon fields, screening parameters, classification of storage sites, and, to some extent, the assessment methodology. This work is more advanced than other studies because it (i) covers all sedimentary basins across Indonesia with levels of estimation ranging from basin-scale for saline aquifers to field-scale for hydrocarbon reservoirs; (ii) classifies the quantitative estimates of CO_2 storage in terms of data availability and certainty of the estimate to provide a measure of comparability and to create classification storage for international usage; (iii) provides a rank of the 128 sedimentary basins in term of CO_2 storage suitability; and (iv) integrates the results into a geographical information system (GIS) for further spatial analysis.

3. Scope of Study

This study aims to perform a geological storage assessment over the sedimentary basins of Indonesia for their CO_2 storage suitability and to estimate the basin-scale storage resources in saline aquifers and the field-scale storage resources in hydrocarbon reservoirs within the selected basins. Figure 1.1 outlines the dispersion of Indonesian sedimentary basins across the country. A high-resolution map is in Appendix A.

Figure 1.1. Indonesia's Sedimentary Basins status as of 2022



Source: Geological Agency, Ministry of Energy and Mineral Resources (2022), *Peta Cekungan Sedimen Indonesia*. Available at: https://www.esdm.go.id/assets/media/content/content-peta-cekungan-sedimen-indonesia-2022.pdf (accessed 1 November 2024).

CO_2 can be geologically stored in various geological settings in sedimentary basins. Oil and gas fields, saline formations, and coal beds are all possible CO_2 storage media within these basins. The CO_2 storage resources in the oil and gas fields are assessed at the level field using reserves data. It is straightforward because they are generally well-defined spatially and in terms of reserves. The estimated CO_2 storage resources in deep saline aquifers are evaluated at the basin level and typically have orders of magnitudes larger than oil and gas fields. The storage potential depends on structural trapping, dissolution, residual trapping, and the average reservoir properties. Although highly uncertain, such theoretical estimation offers essential insights into the potential available for large-scale, long-term storage projects. CO_2 storage in uneconomic coal seams has been identified as an immature technology; there are no clear and accepted definitions of uneconomic coal seams and limited by inadequate data availability. For these reasons, coal seams are excluded in this study.

Basins suitable for safe CO_2 storage are characterised by thick accumulations of sediments, extensive covers of low-porosity rocks acting as seals and structural simplicity. While many basins show such features, many others do not. It is deemed necessary to inject CO_2 at depths greater than 800 m for a hydrostatic pressure gradient and a geothermal gradient of 25ºC/km to meet supercritical conditions of CO_2 at a temperature greater than 31.1ºC and pressure greater than 7.38 Mpa. At these pressures and temperatures, CO_2 behaves like a gas by filling all the available pore volume but has a liquid-like density that increases at supercritical conditions. The higher density of CO_2 leads to higher pore space efficiency, which can be used to store CO2. For safety and efficiency of geological storage reasons, the deep saline aquifers included in this study are limited to a depth between 800 m to 2,500 m.

Given these constraints, not all the 128 sedimentary basins outlined in Figure 1.1 are included in the CO2 storage estimation. Some are too shallow, and others are dominated by rocks with low permeability or poor confining characteristics. A two-stage process for the site screening is applied. The first stage is an elimination process, whereby sites are eliminated from consideration completely. The second stage then looks at the sites that passed the elimination stage to quantify a site's suitability for CO_2 storage compared to other sites.

4. Report Structure

This report contains five chapters, in addition to appendices and an executive summary.

Chapter 1 provides the broad motivation for CCUS and the imperatives that could shape its deployment in Southeast Asia. The chapter also describes the driver for Indonesia to be a CCUS hub in the region, previous studies, and scope of the study.

Chapter 2 presents the geological framework and sedimentary basin of Indonesia. It outlines the western and eastern geological setting of Indonesia and basin development status.

Chapter 3 discusses the methodology used in estimating the CO_2 geological storage resources for hydrocarbon reservoirs at the field level and deep saline aquifers at the basin scale, along with the basin screening methodology for CO_2 storage suitability.

Chapter 4 presents screening and ranking of 128 sedimentary basins in terms of CO_2 storage suitability, the potential of CO_2 storage in deep saline aquifers, and in oil and gas fields and their dispersion across the sedimentary basins of Indonesia. It also provides a geographical information system to visualise the results on the spatial maps.

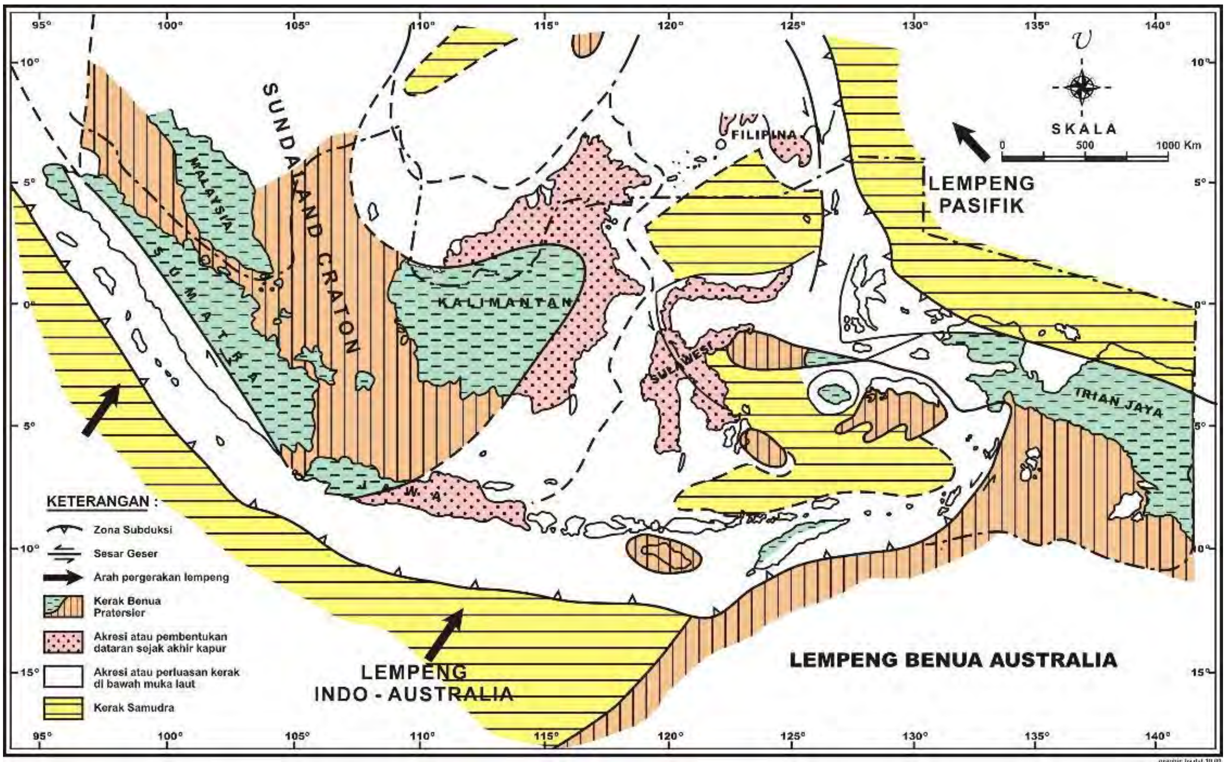
Chapter 5 concludes and gives directions for potential areas of further work that should be explored.

Chapter 2
Geological Framework and Sedimentary Basins of Indonesia

1. Geological Framework of Indonesia

Indonesia is an archipelagic country, comprising more than 17,000 islands, between Asian and Australian continents and between the Indian and Pacific Oceans. It also crosses with a series of volcanoes known as the ring of fire. Its unique position is a result of geological framework complexity, which in general can be divided into two parts: Western Indonesia and Eastern Indonesia. Western Indonesia is the continental crust (Sundaland Craton of Eurasian Plate) surrounded by oceanic crust (the Indo-Australian Plate in the south and the South China Sea in the north). Eastern Indonesia is composed of the oceanic crust (Banda Sea) and is surrounded by the continental crust (Australian Continental Plate) (Figure 2.1).

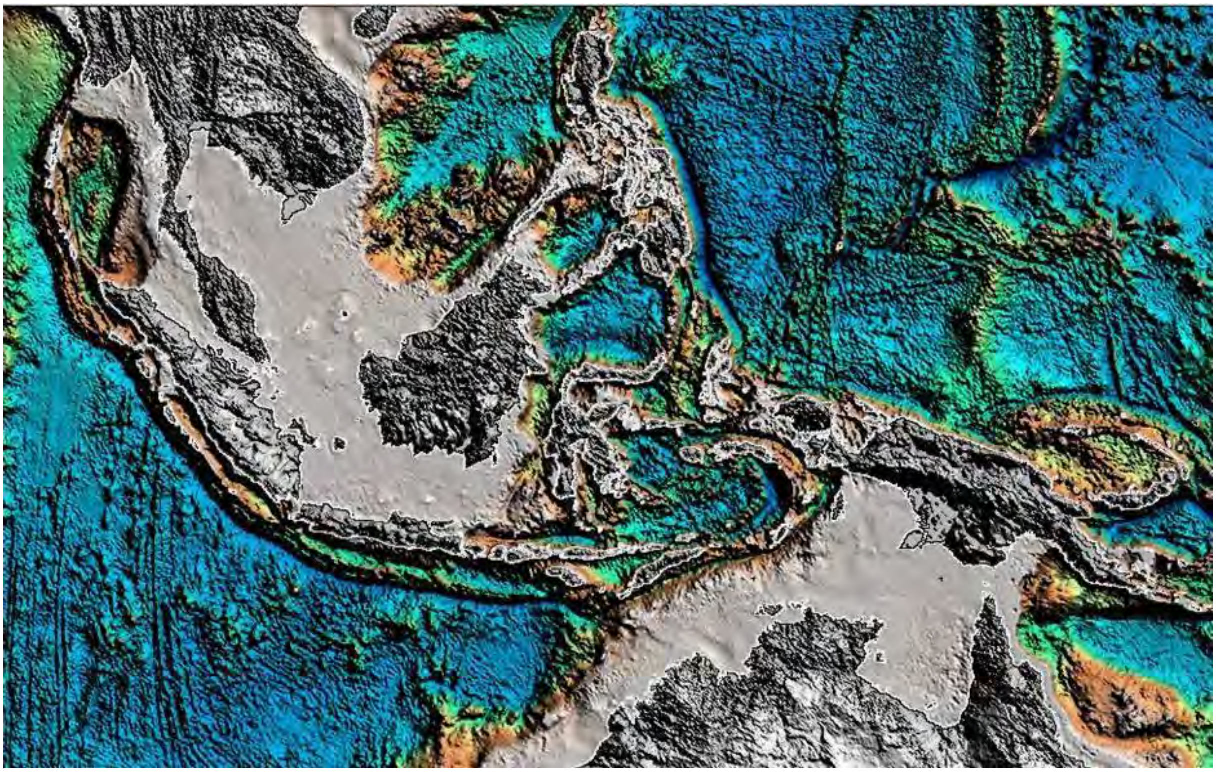
Figure 2.1. Map of Continental Crust and Oceanic Crust in Indonesia



Source: Hadipandoyo et al. (2007).

Based on the topographical relief imaging (Figure 2.2), the continental crust shelf of Eurasian Plate connects the three major islands of Western Indonesia: Sumatra Island, Java Island, and Kalimantan Island. This figure shows Western Indonesia as a part of the Eurasian Continental Crust, in contrast to Eastern Indonesia, which is a mosaic of fragments of the Australian Continental and Asian Continental plates.

Figure 2.2. General Topographic Relief of Indonesia and Surrounding Areas



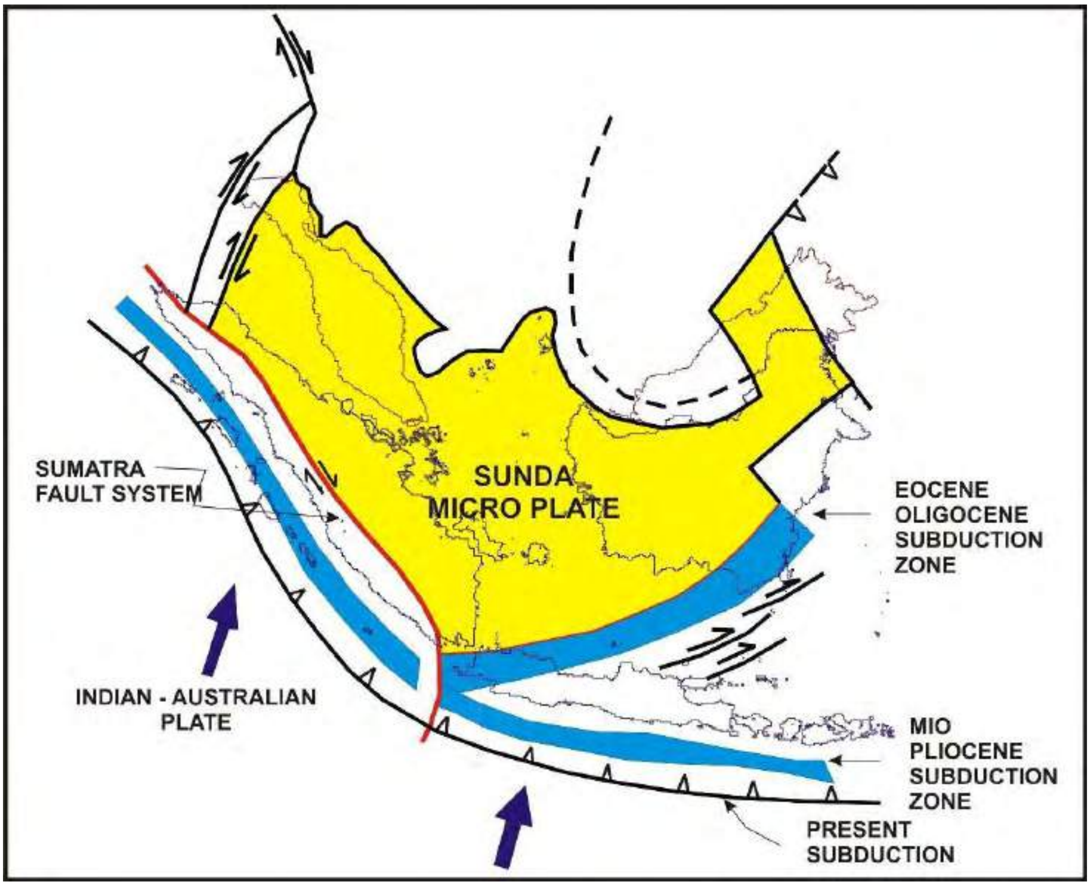
Source: Hadipandoyo et al. (2007).

This tectonic framework may relate to the basin suitability for CO_2 storage such as basin stability, seismicity, and fracture development. For example, the basins located in the continental craton (e.g. Kutei Basin, Natuna Basin) are more stable, has less seismicity, and less fracture than the basin that developed in the subduction related to area (e.g. Simeulue Basin, Timor Basin), where two plates collide, resulting in high seismicity and intensively fracture development.

1.1. Western Indonesia

Two major tectonic events influenced the geology of the Sunda Shelf during the Tertiary Period. The first is the movement of the Indian subcontinent northward from Africa at the end of the Cretaceous, which eventually collided with the Eurasian Plate. The second is the movement of the Australian continental plate and the Pacific Plate during the Neogene (Sudharmono et al., 1997). The collision between India and Eurasia in the Early Tertiary resulted in rotation in Indochina and extension, forming rift basins on the Sunda Shelf during the Paleogene (Daly, Hooper, and Smith, 1987). This movement of India to the north also caused the collision between the Indian Ocean Plate and the edges of the Sunda Shelf (Sumatra, Java, and Kalimantan) in the Late Cretaceous. This collision path connects the islands of Java and Kalimantan (Figure 2.3).

Figure 2.3. Subduction Line between Java and Kalimantan at the End of the Cretaceous Period



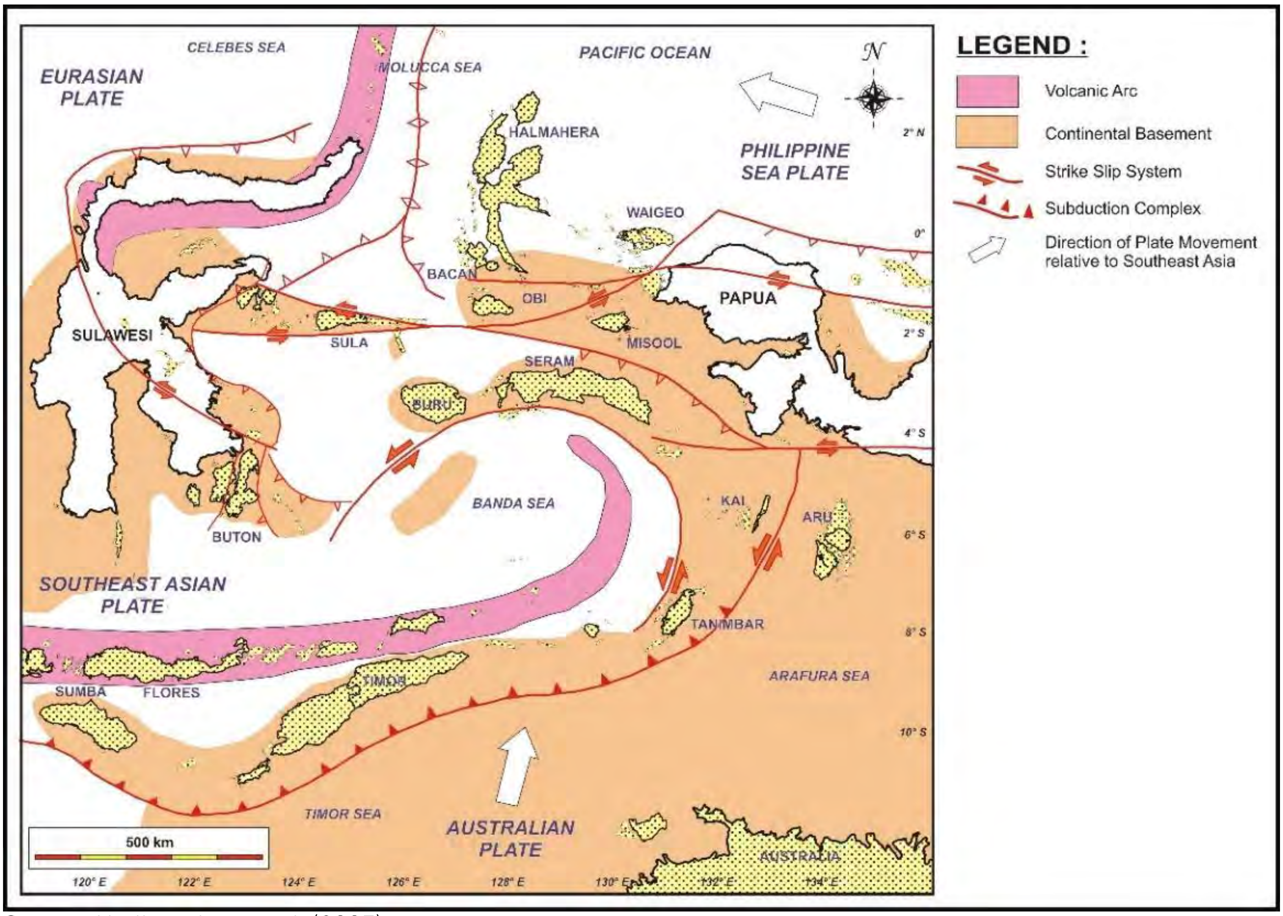
Source: Modified from Adnan, Sukowitono, and Supriyanto (1991).

The movement of the Australian Continental Plate and the Pacific Plate during the Neogene resulted in a collision between the Australian microcontinent (part of Sulawesi) and the eastern edge of Sundaland, located in Kalimantan, and created uplifting of Meratus Mountain in Kalimantan and some strike-slip faults.

1.2. Eastern Indonesia

In general, Eastern Indonesia can be divided into Sulawesi and its surroundings, the Banda Arc, and western Irian (Papua) regions. The regional tectonic elements found in this region, such as the Sorong Fault zone and Banda Trench, are related to plate collision activity between the Pacific/Philippine Plate and the Australian Continental Plate, or between the Asian Plate and the Australian Plate (Figure 2.4). In Eastern Indonesia basins, the Mesozoic rocks mostly occur as sedimentary rocks, while in Western Indonesia region, the Mesozoic rocks are commonly found as metamorphic or metasediment rocks. It is possibly due to tectonic activity that was more active in Eastern Indonesia in the past.

Figure 2.4. Tectonic Framework of Eastern Indonesia



Source: Hadipandoyo et al. (2007).

2. Sedimentary Basins of Indonesia

Since the late 1960s, a significant number of seismic data sets were acquired. Based on these data, several sedimentary basin maps containing 60 sedimentary basins were published (Hamilton, 1979; Pertamina and Beicip-Franlab, 1992a). The status of the basins has been classified into basins with production, basins with hydrocarbon discovery, basins with exploration wells but no discovery, and undrilled basins (Sujanto, 1997; Netherwood, 2000). The outline of the basins was used as a reference by the government and the petroleum industry.

In 2009, the Geological Agency of Indonesia published a map showing 128 sedimentary basins outlined in Indonesia. This basin map was defined based on gravity data supported by sub-surface data, including seismic, magnetic, and surface geological data. In 2022, the Geological Agency updated the map by adding information regarding oil and gas activity. This new version was officially issued by the Ministry of Energy and Mineral Resources in 2022 and became a reference for all stakeholders (Figure 1.1 and Appendix A). The sedimentary basin status is divided into four types based on oil and gas exploration and production activities in each basin. The redefined division is as follows:

1) *Producing basins* are basins that have production wells, totalling 20 basins.
2) *Discovery basins* are basins that have discovered hydrocarbon wells but have not yet produced them, totalling 27 basins.
3) *Prospective basins* are basins that have oil and gas potential, subdivided into:
   a) Basins with potential petroleum system components, seismic data and wells available, which consist of eight basins.
   b) Basins with hydrocarbon seepage and available seismic data. There are four basins of this category.
4) *Unexplored basins* are basins that have not been explored, and are further divided into:
   a) 26 basins that have not been explored with geological, seismic, and non-seismic data
   b) 43 basins that have not been explored with limited data availability.

Maps and legends regarding the distribution of sedimentary basins in Indonesia are shown in Appendix B. The map of 128 sedimentary basins included shallow and young basins, which are non-prolific for CCUS or CCS. But the majority offer a range of good quality reservoir-seal pairs for safety and secure geological CO_2 storage.

Chapter 3
Methodology

Before providing the methodology for estimating CO_2 storage resources in oil and gas reservoirs and deep saline aquifers, a series of concepts and definitions are introduced to establish a common understanding and terminology.

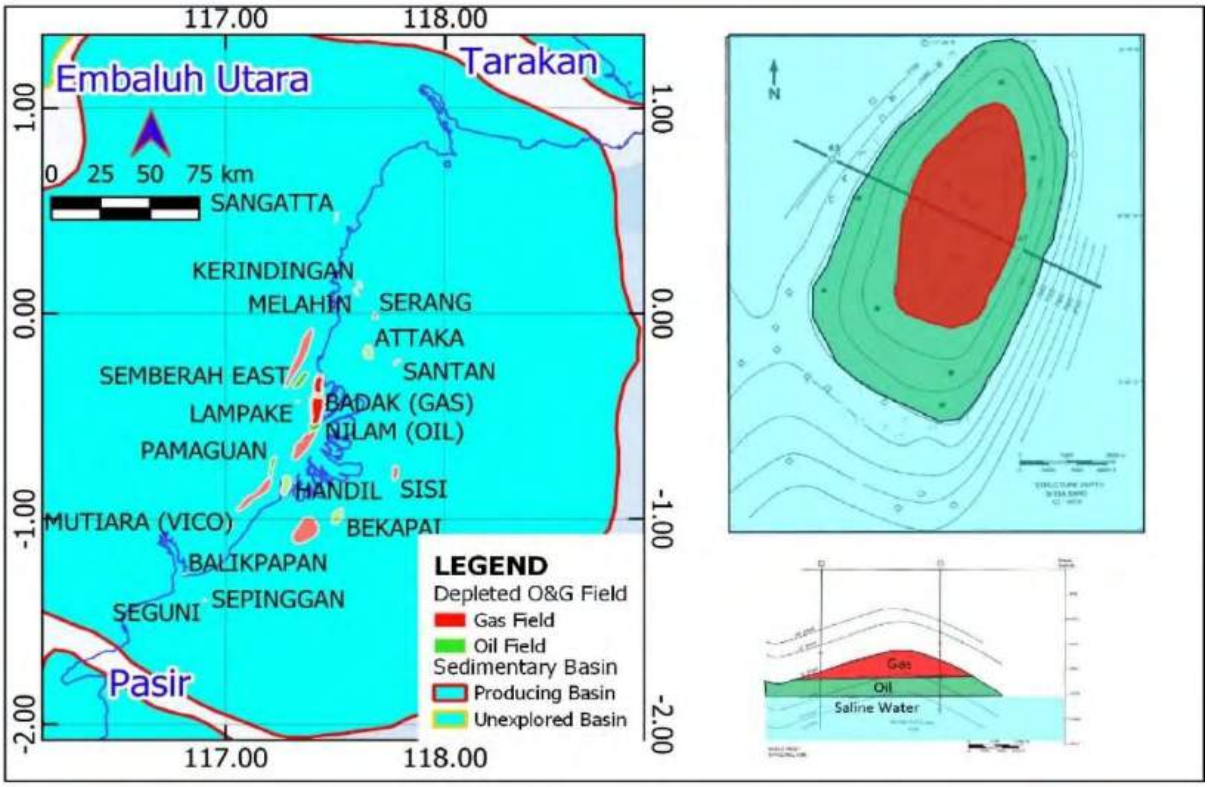
1. Principles of Geological CO_2 Storage

The suitability of sedimentary basins for CO_2 storage depends partly on their location on the continental plate. Basins formed in mid-continent locations or near the edge of stable continental plates are excellent targets for long-term CO_2 storage because of their stability and structure. Such basins are found mostly within the western and eastern Indonesia basins.

In general, geological storage sites must have (i) the capacity to store the intended volume of CO_2 over the lifetime of the operation, (ii) injectivity to accept CO_2 at the rate supplied from the emitter(s), (iii) containment to ensure that CO_2 will not migrate and/or leak out of the storage unit, and (iv) sufficiently stable geological environment to avoid compromising the integrity of the storage site (IEA GHG, 2009; IPCC, 2005). Poor CO_2 storage potential will likely be exhibited by basins that (i) are thin (≤1000 m), (ii) have poor reservoir and seal relationships, (iii) are highly faulted and fractured, (iv) are within fold belts, (v) have strongly discordant sequences, (vi) have undergone significant diagenesis or (vii) have over-pressured reservoirs (IPCC, 2005).

Depending on their specific geological properties, several types of geological formations can be used to store CO_2. The potential CO_2 storage resources in Indonesia that are viable in the near future will be in deep saline aquifers or depleted oil and gas fields. An example of these two geological systems is shown in Figure 3.1 for the Kutai Basin. CO_2 is held-in-place in a storage reservoir through one or more of five basic trapping mechanisms: structural, stratigraphic, solubility, mineral, and residual trapping. The initial dominant trapping mechanisms are structural or stratigraphic trapping, or a combination of the two physical trappings.

Figure 3.1. Map of Kutai Basin's Oil and Gas Fields and Saline Aquifers Viable for CO_2 Storage



Note: A saline aquifer is orders of magnitude larger in size than the oil or gas field.
Source: Created by Authors.

Physical sequestration is a time-dependent seepage process. CO_2 is injected into a deep saline aquifer with a complete impermeable caprock in a supercritical state. The density of supercritical CO_2 is about 600–700 kg/m^3, while the density of brine is around 1,000 kg/m^3. The density difference between the CO_2 and the brine causes the injected CO_2 to flow upward under the action of buoyancy and become blocked by the caprock. Common structural traps include those formed by anticline, folded, or fracture rocks. Stratigraphic traps formed by changes in rock type caused by variation in the setting where the rocks were deposited (CO2CRC, 2008). Care must be taken when CO_2 is injected into these traps not to exceed the allowable overpressure to avoid fracturing the caprock or re-activation faults. The distribution of CO_2 in such traps is mainly affected by viscosity, the capillary force, and gravity.

The phase behaviour and variations of CO_2 properties with temperature and pressure, hence with depth, have implications for CO_2 storage efficiency (IPCC, 2005). The volume required to store the same mass of CO_2 decreases significantly with increasing depth (Figure 3.4b). Hence, the optimum depth is one that maximises the storage and, at the same time, minimises the cost of well drilling and CO_2 compression and injection into the depth. Owing to the strong compressibility of CO_2, the density of CO_2 injected into a saline aquifer will gradually increase and remain largely stable with increasing depth. In contrast, the density of brine is correlated negatively with buried depth (Luo et al. (2022). The decrease in the density difference promotes the ability of the caprock to block the CO_2

plume at higher height, which improves storage capacity. Figure 3.4 suggests that the optimum depth varies from 800 m to 2,500 m. Any depth greater than that will be less efficient and more costly.

Residual trapping occurs when the CO_2 is trapped in the pore space as a residual immobile phase by capillary forces. At the tail of the migrating CO_2 plume, imbibition processes are dominant as the wetting phase of formation water imbibes behind the non-wetting phase of migrating CO_2. When the concentration of the CO_2 falls below a certain level, it is trapped by capillary pressure forces and ceases to flow. Therefore, a trail of residual, immobile CO_2 is left behind the plume as it migrates upward. Residual CO_2 saturation values vary between 5%–30% based on typical relative permeability curves. Over time, the residually trapped CO_2 dissolves into the formation water.

Solubility trapping relates to the CO_2 dissolved into the formation water. Carbon dioxide solubility increases with increasing pressure and decreases with increasing temperature and water salinity. CO_2 may mix with, and then dissolve, in formation water through the processes of diffusion, dispersion, and convection. Residual trapping occurs when the CO_2 becomes trapped in pore space as a residual immobile phase by capillary force. Solubility trapping forms a denser fluid that may sink to the bottom of the storage formation. Depending on the rock formation, the dissolved CO_2 may react chemically with the surrounding rocks to form stable minerals, known as mineral trapping.

Mineral trapping results from the precipitation of new carbonate minerals (Gunter et al., 1993). This storage mechanism is the most permanent of the trapping types discussed as it renders the CO_2 immobile. The timescale for mineral precipitation is typically long, of the order of tens to thousands of years, depending on the initial minerals present. Siliciclastic reservoirs are favoured over carbonate reservoirs, in particular calcium-, magnesium-, or iron-rich siliciclastic reservoirs, as they have the best potential for mineral trapping of CO_2.

The type of trapping that occurs, and when, is dependent on the dynamic flow behaviour of the CO_2 and the timescale involved. With increasing time, the dominant storage mechanism will change and typically the storage security also increases. The CO_2 storage and how the trapping mechanism might alter over time (IPCC, 2005). For example, the initial storage mechanism will be dominantly physical structural and stratigraphic trapping of the immiscible-phase CO_2. With increasing time and migration, more CO_2 is trapped residually in the pore space or is dissolved in the formation water, increasing storage security. Finally, mineral trapping may occur by precipitation of carbonate minerals after the geochemical reaction of the dissolved CO_2 with the host rock mineralogy, permanently trapping the CO_2 (IPCC, 2005).

2. Classification of CO_2 Storage Resources

A CO_2 storage resource is the quantity (mass or volume) of CO_2 that can be stored in a geologic formation. Resource assessments estimate total storable quantities in known, yet-to-be-discovered geologic formations. Resource evaluations focus on those quantities that potentially can be used for commercial storage. A CO_2 storage resources management system (SRMS) provides a consistent approach to estimating storable quantities, evaluating development projects, and presenting results within a comprehensive classification framework. Such a system must consider technical and commercial factors impacting the project's economic feasibility, productive life, and related cash flows.

The CO_2 SRMS is developed to create a consistent set of definitions, a classification system for international usage, as well as provide a measure of comparability. The established use and acceptance of the petroleum resources management system (PRMS) provided the initial template for adaptation to the SRMS document. The PRMS classification concerns the commercial viability of hydrocarbon accumulations. The basis of the SRMS classification scheme is the accessible pore volume in a geologic formation where CO_2 could be stored. Evaluation of all CO_2 storage resources in this study is conducted in the context of the SRMS system (Figure 3.2). The relevant definitions are given below (SPE, 2017).

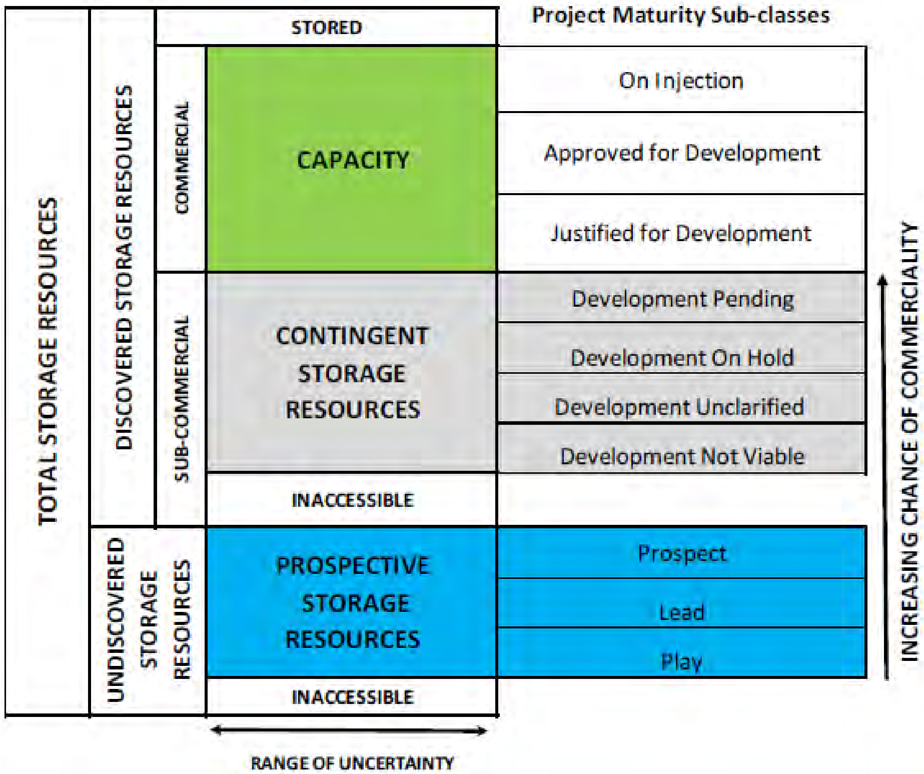
Total Storage Resources is the quantity of storage estimated to exist in geologic formations. It includes that quantity of storage estimated, as of a given date, to be possible in known and characterised geologic formations before injection, plus those estimated quantities in undiscovered or uncharacterised geologic formations.

Discovered Storage Resources refer to the estimated quantity of total storage resources, as of a given date, in which the potential for storage has been ascertained within an assessed geologic formation.

Stored refers to the quantity of discovered storage resources that has been exploited by a given date: This equates to the cumulative quantity of CO_2 injected and stored. While all storage resources are estimated, and stored is measured in terms of CO_2 metering specifications, the total injected quantities (CO_2 plus associated injectants) are also measured, as required in support of engineering analyses.

Storage Capacity refer to quantities of total storage resources anticipated to be commercially accessible in the characterised geologic formation by application of development projects from a given date forward under defined conditions. Commercial storage resources must further satisfy four criteria: (i) the target geologic formation must be discovered and characterised (including containment); (ii) it must be possible to inject at the required rates; (iii) the development project must be commercial; and (iv) the storage resource must remain, as of the evaluation date (i.e. not previously used for storage), on the development project(s) applied. Commercial storage resources are further categorised according to the level of certainty associated with the estimates and may be sub-classified based on project maturity and/or characterised by development and injection status.

Figure 3.2. A Graphical Representation of the SPE Storage Resources Management System



SPE = Society of Petroleum Engineers.

Source: SPE (2017).

Contingent Storage Resources are quantities of total storage resources estimated, as of a given date, to be potentially accessible in known geologic formations. However, the applied projects are not yet considered mature enough for commercial development because of one or more contingencies. Contingent storage resources must be discovered (characterised) and may include projects, for example, for which there are no viable CO_2 sources currently, and in which project value is insufficient to support development, permitting is still incomplete, commercial storage is dependent on technology under development, management is not committed, or evaluation of the geologic formation is insufficient to assess commerciality. Contingent storage resources are further categorised according to the level of certainty associated with the estimates and may be sub-classified based on the project maturity and/or characterised by their economic status and permitting/stakeholder status.

Undiscovered Storage Resources are the estimated quantity of total storage resources, as of a given date, in which the suitability for storage has not been ascertained within the target geologic formation.

Prospective Storage Resources refer to the quantity of undiscovered storage resources estimated, as of a given date, to be potentially accessible within undiscovered geologic formations or uncharacterised parts of discovered geologic formations by application of future exploration/development projects. Prospective storage resources have both an associated chance of discovery and a chance of development. Prospective storage resources are subdivided per the level of certainty associated with accessible estimates, assuming their discovery and development, and may be sub-classified based on the project maturity.

Inaccessible Storage Resources are the estimated portions of discovered or undiscovered storage resources, as of a given date (i.e. the time of the evaluation), that are not usable by future storage development projects. A portion of these inaccessible storage resources may be used for storage in the future as commercial or regulatory circumstances change or technological developments occur. The remaining portion may never be used for storage resulting from physical/societal constraints of the storage location, both surface and subsurface.

Resources are initially estimated using the above uncertainty-range forecasts by applying technical constraints related to wells and facilities. These technical forecasts then apply the additional criteria (economics and license cutoffs are the most common) to determine the storable quantities attributed to resource classes: Capacity, Contingent Resources, and Prospective Resources.

Evaluators may assess storable quantities and categorise results by uncertainty with the deterministic-incremental approach, the deterministic-scenario (cumulative) approach, or probabilistic methods. In many cases, a combination of approaches is used.

For Capacity, the general cumulative terms low/best/high estimates are denoted as 1P/2P/3P, respectively. The associated incremental quantities are termed Proved, Probable, and Possible. Capacity is a subset of, and must be viewed within the context of, the complete resource-classification system. While the categorisation criteria are proposed specifically for Capacity, in most cases, they can be equally applied to Contingent and Prospective Storage Resources, conditional upon satisfying the requirements for discovery and/or development.

Quantities between classes and subclasses should not be aggregated without considering the varying degrees of technical uncertainty and commercial likelihood involved with their classification(s).

For Contingent Storage Resources, the general cumulative terms low/best/high estimates are used to determine the resulting 1C/2C/3C, respectively. The terms C1, C2, and C3 are defined for incremental quantities of Contingent Resources.

For Prospective Storage Resources, the general cumulative terms low/best/high estimates also apply and are used to determine whether the resulting 1U/2U/3U still apply. No specific terms are defined for incremental quantities within Prospective Storage Resources.

The following points summarise the definitions for each capacity category, in terms of both the deterministic-incremental approach and scenario approach, and provide the probability criteria if probabilistic methods are applied.

Proved Capacity (P1) - the storable quantities that can be estimated with reasonable certainty to be commercially used for storage by analysis of geoscience and engineering data from a given date forward and under defined economic conditions, operating methods, and government regulations. If deterministic methods are used, the term 'reasonable certainty' is intended to express a high degree of confidence that the quantities will be stored. If probabilistic methods are used, there should be at least a 90% probability that the quantities stored will equal or exceed the estimate.

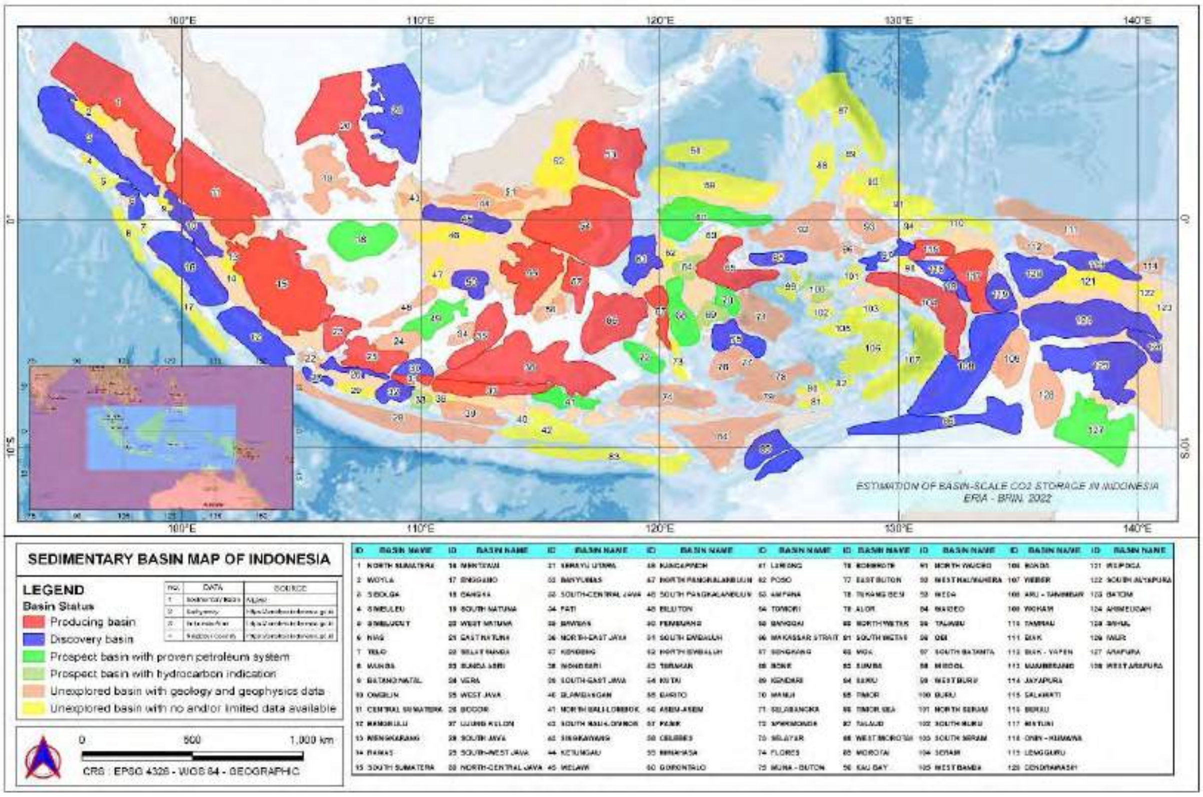
Probable Capacity (P2) - the additional storable quantities, which analysis of geoscience and engineering data indicate, will less likely be used for storage than Proved Capacity, but more certain to be stored than Possible Capacity. It is equally likely that the actual remaining quantities stored will be greater than or less than the sum of the estimated Proved plus Probable Capacity (2P). When probabilistic methods are used, there should be at least a 50% probability that the actual-stored quantities will equal or exceed the 2P estimate.

Possible Capacity (P3) - the additional storable quantities, which analysis of geoscience and engineering data suggest, will less likely be used for storage than Probable Capacity. The total ultimately stored quantities from the project have a low probability of exceeding the sum of Proved plus Probable plus Possible (3P) Capacity, which is equivalent to the high-estimate scenario. When probabilistic methods are used, there should be at least a 10% probability that the actual quantities stored will equal or exceed the 3P estimate.

3. Basin Screening and Ranking for CO_2 Storage Suitability

Geological media that can be used for CO_2 storage are in sedimentary basins. However, sedimentary basins do not necessarily contain the proper geological media storage, and these media may not satisfy minimum qualitative criteria such as depth for safe CO_2 storage. Therefore, sedimentary basins are not all equally prospective for CO_2 storage. A basin screening assessment for CO_2 storage potential in the Indonesia sedimentary basins is conducted to identify the most prospective basins. It represents the first step in identifying the best regions for geological storage of CO_2 and for guiding future site selection. Figure 3.3 shows 128 sedimentary basin outlines in Indonesia.

Figure 3.3. Indonesia's Sedimentary Basin Outlines (Total of 128 Basins)



Source: Created by Authors. The Sedimentary Basin Map provided by the Geological Agency, Ministry of Energy and Mineral Resources (2022).

Several common methodologies have been developed for screening CO_2 storage suitability at the basin-scale level. Bachu (2003) was one of the first to propose criteria for assessing and ranking sedimentary basins in terms of their suitability for CO_2 geological storage. According to this evaluation method, the basin suitability is assessed using 15 criteria and can be grouped into qualitative geological and practical categories transformed into quantitative values (Malo and Bedrad, 2012). Geological criteria include tectonic setting, size and depth of the basin, faulting and fracturing, hydrogeology, geothermal regime, hydrocarbon potential, maturity of exploration, presence of coal and coalbed methane, and salt. Practical criteria are the basin's on-/off-shore setting, climate, accessibility, infrastructure, and CO_2 sources.

In-depth screening to evaluate the practicality of storing CO_2 in an appropriate region considering key geological indicators from the point of reservoir properties and caprock properties has also been introduced (Chadwick et al., 2008). Reservoir properties include static and dynamic storage potential, reservoir depth, thickness, porosity, permeability, sea integrity, and salinity. Caprock properties include factors of lateral continuity, thickness, and capillary entry pressure. Qualifiers and threshold values for each criterion have been suggested to ensure the safety and security of CO_2 storage.

According to developed screening methodologies, to be deemed suitable for geological storage of CO_2, a basin must meet a range of criteria that can be grouped into a set of categories consisting of safety and security, storage and injectivity, legal and regulatory issues, economics, and public acceptance (IEA, 2009). This forms the basis for classifying screening criteria as either eliminatory or selection based. Eliminatory criteria effectively rule out a basin for selection if the criteria are not met, whereas selection criteria quantify a site's suitability for storage.

Due to some of the 128 Indonesia sedimentary basins being too shallow and considering the geological tectonic complexity that exists from the western to the eastern Indonesia regions resulting in variously suited for CO_2 storage, a synthesis of eliminatory and selection screening criteria has been applied in this study to evaluate the overall suitability of Indonesia sedimentary basins for CO_2 storage. The elimination process employed a depth of 800–2,500 m to eliminate unsuited basins for CO_2 geological storage. The selection process then looks at the sedimentary basins that passed the elimination stage to quantify a basin's suitability for CO_2 storage compared to other sites.

A set of 16 criteria reflecting the unique geology of Indonesia has been defined for the selection process. The 16 criteria are grouped into four categories related to data availability, storage potential, security, and environment to determine its relative importance among the set of criteria. The relative importance of each criterion is made based on the experiences and judgement. A pairwise comparison approach is then applied to obtain the weight of each criterion. Table 3.1 summarises the proposed screening process criteria applied in this study and its data source.

Table 3.1. Developed Criteria for Assessing CO_2 Storage Suitability of Indonesia's Sedimentary Basins

Category	Criteria	Reference - Database
Data Availability	1. Basin Maturity	Geological Agency (2009, 2022)
Storage Potential	2. Basin Sise	Geological Agency (2009, 2022)
	3. Reservoir Porosity (%)	IPA (2006); SKK MIGAS - LAPI ITB (2008); LEMIGAS-SKK Migas (2015)
	4. Reservoir Thickness (m)	National Geoscience Data Center - British Geological Survey (NGDC - BGS), IPA (2006), and SEAPEX
	5. Sediment Thickness (m)	Darman and Yuliong (2020); Pertamina-Unocal (1997)
	6. Reservoir Temperature	NGDC; IPA (2006), SEAPEX; IPA; SKK MIGAS - LAPI ITB (2008); LEMIGAS Internal Database
	7. Geothermal Gradient $^oC/km$	NGDC - BGS; IPA (2006); and SEAPEX.
Storage Security	8. Seal Thickness (Number of Seal)	IPA (2006); SKK MIGAS - LAPI ITB (2008); LEMIGAS – SKK Migas (2015)

Category	Criteria	Reference - Database
	9. Tectonic Setting	Geological Agency (2009)
	10. Seismicity Max (pga)	Darman and Yuliong (2020); Indogeo (2023)
	11. Earthquake Magnitude	Geological Agency (2009); USGS website
	12. Volcanism (km)	Geological Agency (2009)
	13. Fault and Fracture Intensity	Shuttle Radar Topographic Mission (SRTM); Bathimetry Data
	14. Trap Development	SKK MIGAS - LAPI ITB (2008)
Environmental	15. Basin Location (on/off-shore-water depth)	Geological Agency (2009), Bathymetry Data (Topex)
	16. Hydrology	Geological Agency (2009); The Ministry of Public Works and Housing

Source: Created by Authors. Data are derived from multiple sources.

Each criterion is briefly described as follows.

1) *Basin Maturity*. Maturity criteria relate to the volume and distribution of data, especially seismic and drilling data. Based on the distribution of data and the status of the basin, the maturity criteria are divided into five classes: production basins, discovery basins, prospect basins with a petroleum system, prospect basins with seepage, and unexplored basins.

2) *Basin Size*. Basin size criteria affect a basin's capacity to function as a CO_2 storage; the wider a basin, the greater its storage opportunities.

3) *Reservoir Porosity*. The porosity value of the reservoir rock at the basin scale can be obtained from the results of a study of the basin-scale petroleum system, both from outcrop data and well data if there are already developed oil and gas fields in the basin.

4) *Reservoir Thickness*. Reservoir rock thickness criteria are also related to the production of the basin's petroleum system or oil and gas field data.

5) *Sediment Thickness*. The thickness of the sediment that fills the basin is related to the depth of the basin, so the thickness of this sediment correlates with the depth of the basin. A basin with a depth of more than ~800 m will significantly increase the efficiency of CO_2 storage capacity because CO_2 will be in a supercritical state where its density increases. The actual depth for CO_2 to reach supercritical conditions depends on the temperature and pressure of the basin and the depth of the water table. Generally, 800 m is the typical minimum depth of the average reservoir.

6) *Reservoir Temperature*. Reservoir temperature is obtained from drilling data or geothermal gradient data in general. The hotter the reservoir conditions, the lower the ability to store carbon dioxide.

7) *Geothermal Gradient*. The subsurface temperature in a basin depends on in situ geothermal conditions and surface temperature. Geothermal conditions impact storage volume: the colder a basin, the higher the density of CO_2 so that more CO_2 can be stored in the same unit volume of rock. Sediment basins with a high- temperature gradient have a relatively lower storage capacity and efficiency than basins with a low-temperature gradient.

8) *Seal Thickness*. This is the most crucial prerequisite in selecting storage sites. A good reservoir must have vertical containment with low-permeability rocks. The lithology that fills a basin and its stratigraphic conditions are essential in good reservoir and seal quality. A simple stratigraphic column or chronostratigraphic chart can be used to quickly and easily screen for quality, presence, distribution, and frequency of reservoir seal pairs. The thicker the insulating sediment, the better the storage conditions are expected to be.

9) *Tectonic Setting*. This criterion is based on the tectonic framework of a basin. The tectonic conditions of sedimentary basins are greatly influenced by the dynamics of the basin, which are controlled by the current tectonic position based on the plate tectonic theory.

10) *Seismicity Max*. It is the most critical component in the risks associated with containment. Seismically active areas tend to experience earthquakes and have a large potential for leakage. The tectonically unstable areas are the subduction system's fore-, intra-, and back-arc basins. Although seismicity is the most fundamental criterion in assessing the suitability of a storage site, accumulation of hydrocarbons can be found in seismically active areas, which means the area may have potential for carbon dioxide storage.

11) *Earthquake Magnitude*. Earthquake criterion is also a special condition that must be considered for Indonesia. The intensity of seismicity in Indonesia, including both tectonic and volcanic earthquakes, is quite high. Indonesia, a meeting area of three continental plates, is indeed an area prone to earthquakes.

12) *Volcanism*. This criterion is proposed as a characteristic of basin conditions in Indonesia, which are heavily influenced by volcanism. Indonesia is a country that has the most volcanoes in the world. This volcanic system is referred to as the ring of fire; Indonesia is included in or part of the Pacific Circum and Mediterranean Circum. So, the paths of volcanoes are included as a criterion to be considered in terms of the safety of CO_2 storage based on their distance.

13) *Fault and Fracture Intensity*. This criterion determines containment and capacity issues. In addition, it also depends on the nature of a fault: the more faults there are in an area, the greater the risk of containment breaches through conductive faults and fractures. Areas with intense faults and fractures are categorised as low class and are

unsuitable for storage of CO_2 gas because they are prone to leaks, while those that are not intense will be safer.

14) *Trap Development*. Trap development is closely related to the calculation of storage capacity. Structural traps are preferred compared to stratigraphic traps.

15) *Basin Location (onshore/offshore)*. Indonesian sedimentary basins vary in location between onshore and offshore/sea. When in the sea, it is associated with the condition of the basin's sea depth, an important indicator of economic considerations, which are usually easier to implement onshore and cheaper to build. On the other hand, when viewed from the perspective of public perception and land use, offshore is more desirable as CO_2 storage so it is included in the maximum class.

16) *Hydrogeology*. Hydrogeology describes an aquifer's dynamic natural flow system that has the potential to contribute to hydrodynamic trapping mechanisms. Saline aquifers that are shallow and have a short flow system are categorised as not meeting the requirements to keep CO_2 in a supercritical state.

Furthermore, each criterion is classified into five classes by considering its suitability for the CCUS/CCS application. The higher the class, the greater the potential for CCUS/CCS application. Qualifiers or threshold values of each class are assigned quantitative and/or qualitative considerations. Qualitative assignment uses the formula maximum value minus minimum value divided by the number of classes, whereas qualitative assignment relies on geological analysis. Table 3.2 presents the basin-scale criteria and classes for CO_2 storage specifically developed for Indonesian sedimentary basins.

Table 3.2. Criteria and Classes for Screening Indonesia's Sedimentary Basin-scale CO_2 Storage Suitability

No	Criteria	1	2	3	4	5
1	Basin maturity	Basin with no/limited data availability	Unexplored basin with geology & seismic data	Prospect basin	Discovery basin	Producing basin
2	Basin size (km^2)	<29,900	29,900–58,500	58,500–87,200	87,200–115,900	>115,900
3	Reservoirs porosity (%)	No data	<10.7	10.7–15.4	15.4–20.1	>20.1
4	Reservoirs thickness (m)	No data	0–50	50–100	100–150	>150
5	Sediment thickness (m)	1,001–2,000	2,001–3,000	3,001–4,000	4,001–5,000	>5,001
6	Reservoir temperature (^oC)	75–200	35–200	35–150	35–100	35 - 75
7	Gradient geothermal ^oC/km	>5	4–5	3–4	2–3	<2
8	Seal	No data	with one seal formation	with two seal formations	with three seal formations	with more or as many as four seal formations
9	Tectonic setting	Fore arc, trench (convergence)	Trans tension (Strike-slip) intermontane, oceanic, marginal oceanic (cratonic)	Rifting valley (Intermontane - cratonic) & rifting valley (Fore arc-cratonic convergence), foreland	Passive margin deltaic cratonic and foreland cratonic convergence, rifting valley back arc and foreland cratonic convergence, back-arc convergence	Passive margin cratonic, Passive Margin rifting valley cratonic, rifting valley cratonic, rifting valley passive margin cratonic

No	Criteria					
		1	2	3	4	5
10	Seismicity max. (pga)	>0.5	0.4–0.5	0.3–0.4	0.2–0.3	0.1–0.2
11	Earthquake magnitude (MMI)	5– >8	4–8	4–7	4–5	<4
12	Volcanism (km. distance)	<50	50–100	100–150	150–200	>200
13	Fault & fracture intensity	>4.211	3.21–4.211	2.140–3.21	1.07–2.140	<1.07
14	Trap development	No data	Combine Stratigraphy–Structural	Stratigraphy	Fault	Fold
15	Basin location/water depth	Offshore (>500 m)	Offshore (>500 m)	Onshore–Offshore (>100 m)	Onshore–Offshore (>100 m)	Onshore
16	Hydrology	Offshore	Dominant offshore and low productivity basins (scarce groundwater) and groundwater basins with low continuity and groundwater can be obtained with small discharges.	Aquifers with productive local productivity	Dominant groundwater basins with moderate aquifer productivity.	Dominant high productivity Groundwater basin with wide distribution

Source: Produced by this study.

4. Estimation of CO_2 Storage in Deep Saline Aquifers

5.

Saline aquifers are porous and permeable reservoir rocks containing saline fluid in the pore spaces between the rock grains. They occur at depths greater than aquifers that contain potable water. Usually, due to its high saline proportion and its depth, the water contained cannot be technically and economically exploited for surface uses (Bentham and Kirby, 2005).

CO_2 storage resource estimation of saline aquifers represents the fraction of pore volume in a formation that can be occupied by injected CO_2. A saline aquifer is porous and has permeable rocks, such as sandstone and carbonate rocks, which can include more than one named geologic formation or defined as only part of a formation (DOE-NETL, 2007, 2008). These criteria include the following but are not limited to (i) pressure and temperature conditions; (ii) isolation from shallow potable groundwater, other strata, soils, and the atmosphere; and (iii) caprock or seal capillary entry pressure (Bachu, et al. 2009).

The storage of CO_2 in saline aquifers is limited to sedimentary basins exceeding 800 m. The 800 m cutoff attempts to select a depth that reflects pressure and temperature that yields high density liquid or supercritical CO_2 (Figure 3.4). This depth can vary significantly from location to location (DOE-NETL, 2008; Goodman et al., 2011).

In this study, the resource calculation of basin scale CO_2 storage in saline aquifers was conducted based on the volumetric method adopted from the United States (US) Department of Energy National Atlas I and II (DOE-NETL, 2007 and 2008). The volumetric method is typically used when limited or no specific data are available (Frailey, 2009). The volumetric equation is:

$$M_{CO_2} = A \times h_g \times \phi_{tot} \times \rho_{CO_2} \times E \times C_{fs} \qquad (3.1)$$

The basinal area (A), gross formation thickness (h_g), and total porosity (φ_{tot}) terms account for the total bulk volume of pore space available. The CO_2 density (ρ_{CO2}) converts the reservoir volume of CO_2 to mass. Rather than explicitly using an irreducible water saturation parameter, the storage efficiency factor (E) reflects the fraction of the total pore volume filled by the injected CO_2. Table 3.3 summarises the terms shown in Eq. (3.1).

Table 3.3. Parameters for CO_2 Storage Resources Estimation in Saline Aquifers

Parameter	Unit	Description
M_{CO2}	Mt	Estimate of saline formation CO_2 storage resources in million tones, Mt.
A	km^2	Basinal area that defines the basin being assessed for CO_2 storage resources estimation
h_g	m	Gross thickness of saline formations for which CO_2 storage is assessed within the basin defined by A
ϕ_{tot}	fraction	Average porosity of entire saline formation over thickness h_g

Parameter	Unit	Description
ρ_{CO2}	kg/m^3	Density of CO_2 evaluated at pressure and temperature that represents storage conditions averaged over the depth range associated with hg
E	fraction	CO_2 storage efficiency factor that reflects a fraction of the total pore volume that is filled by CO_2
C_{ff}	Mt/kg x m^3/km^3	A conversion factor to change the set of units in Eq. (2.5) to million tones.

Source: Authors.

The CO_2 storage efficiency factor is a function of geologic parameters such as area ($E_{An/At}$), gross thickness ($E_{hn/hg}$), and total porosity ($E_{\varphi e/\varphi tot}$). Displacement efficiency components include areal (E_A), vertical (E_L), gravity (E_g), and microscopic (E_d). The storage efficiency factor (E) adjusts total gross thickness to net gross thickness, total area to net area, and total porosity to effective (interconnected) porosity containing CO_2. Without E, Equation 3.1 presents the total pore volume or maximum upper limit to storage CO_2. The inclusion of E provides a means of estimating storage volume for a basin with the level of knowledge (uncertainty) in specific parameters determining the type of CO_2 storage capacity estimated. The individual parameters are required to estimate the CO_2 storage efficiency factor for saline formations. Eq. (3.2) gives the storage efficiency factor, and Table 3.4 summarises the parameters given in the equation (DOE - NETL, 2007).

$$E = E_{An/At} \times E_{hn/hg} \times E_{\phi e/\phi tot} \times E_A \times E_L \times E_g \times E_d \quad (3.2)$$

Table 3.4. Parameters Included in Storage Efficiency Factor for Saline Aquifers

Parameter	Symbol	Description
Terms used to define the entire basin/region pore volume		
Net to total area	A_n/A_t	Fraction of total basin/region area that has a suitable formation present
Net to gross thickness	h_n/h_g	Fraction of total geologic unit that meets minimum porosity and permeability requirements for injection
Effective to total porosity ratio	ϕ_e/ϕ_{tot}	Fraction of total porosity that is effective
Terms used to define the fraction of pore volume accessed by CO_2 from injection wells.		
Areal displacement efficiency	E_A	Fraction of immediate area surrounding an injection well that can be contacted by CO_2, most likely influenced by areal geologic heterogeneity such as faults or permeability anisotropy
Vertical displacement efficiency	E_L	Fraction of vertical cross section (thickness), with the volume defined by the area (A) that can be contacted by the CO_2 plume from a single well

Parameter	Symbol	Description
Gravity	E_g	Fraction of net thickness that is contacted by CO_2 because of the density difference between CO_2 and brine
Microscopic displacement efficiency	E_d	Portion of the CO_2-contacted, water-filled pore volume that can be replaced by CO_2. Ed is directly related to irreducible water saturation in the presence of CO_2 or residual CO_2 saturation, dependent on position within the plume

Source: Authors.

Efficiency for saline aquifers as estimated by Monte Carlo sampling with additional supported data revealed *E* factor range between 0.40% and 5.5% over the 10^{th}–90^{th} probability range (DOE-NETL, 2007; IEA GHG, 2009; Goodman et Al., 2011). Table 3.5 presents *E* (geologic and displacement) for different general lithology (Goodman et. al, 2011), where E_A x E_L x E_g is combined into a single volumetric displacement term, E_V (IEA GHG, 2009).

Table 3.5. Saline Aquifer Efficiency Factors for Geologic and Displacement Terms

Lithology	$E = E_{An/At} \times E_{hn/hg} \times E_{\phi e/\phi tot} \times E_V \times E_d$		
	P_{10} (%)	P_{50} (%)	P_{90} (%)
Sandstone	0.51	2.0	5.4
Dolomite	0.64	2.2	5.5
Limestone	0.40	1.5	4.1

Source: Goodman et al. (2011).

In the case where net-to-total area $E_{An/At}$, net-to-gross thickness $E_{hn/hg}$, and effective-to-total porosity $E_{\phi e/\phi tot}$ are known for a basin, the geologic efficiency values can be used directly in Eq. (3.1). In this instance, only the displacement efficiency factor is needed, which ranges between 7.4% and 26% over the 10% and 90% probability range (Table 3.6).

Table 3.6. Saline Aquifer Efficiency Factors for Displacement Terms

Lithology	$\mathbf{E = E_V \times E_d}$		
	P_{10} (%)	P_{50} (%)	P_{90} (%)
Clastic	7.4	14.0	24.0
Dolomite	16.0	21.0	26.0
Limestone	10.0	15.0	21.0

Source: Goodman et al. (2011).

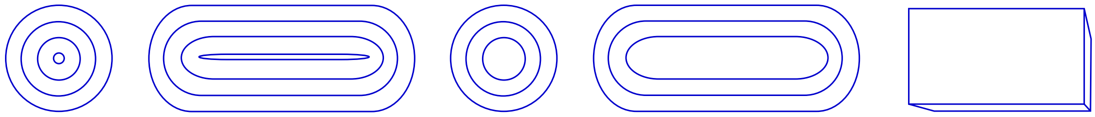
In the previous versions of the Carbon Sequestration Atlas of the US and Canada, the geologic and displacement parameters were not based on documented ranges (DOE-

NETL, 2006; 2008). These saline formation efficiency factors ranged between 1% and 4% over the P_{15} and P_{85} percent probability range (DOE-NETL, 2006; 2008).

The following describes the steps for basin-scale CO_2 storage resources estimation conducted in this study.

1) Collecting data to build a sedimentary basin database. Data were collected from the Sedimentary Basin Database of the Geological Agency, a special publication by the Indonesian Petroleum Association (IPA), such as the Geothermal Gradient Map of Indonesia, Indonesia Oil and Gas Field Atlas, published papers, and LEMIGAS internal reports
2) Creating a basin table for data selection
3) Identifying reservoir formation for saline aquifer candidates in each basin from the sedimentary basin database/table
4) Data for CO_2 storage estimation of producing and discovered basins are taken from subsurface data from wells, oil, and gas reservoirs.
5) Considering limited data availability, applying a geometric correction to reduce the uncertainty. This geometric correction is conducted by using a trap geometry multiplier introduced by White (1987) to calculate the bulk volume of the saline aquifer. The trap geometry multiplier reduces closure height or reservoir thickness to the effective average for the whole closure area. Figure 3.4 lists the multipliers for different trap geometry and the range ratio of reservoir thickness to the height of closure.

Figure 3.4. Trap Geometry Multiplier for Different Types of Closure and Range Ratio of Reservoir Thickness to Height of Closure



RESERVOIR THICKNESS / HEIGHT OF CLOSURE	DOME, CONE, PYRAMID	ANTICLINE, PRISM, CYLINDER		FLAT-TOP DOME	FLAT-TOP ANTICLINE		BLOCK, VERTICAL, CYLINDER
L/W	1	2	10	1	2	10	
1.0	0,34	0.42	0.49	0.59	0.66	0.74	1.0
0.9	0.37	0.46	0.54	0.63	0.71	0.77	1.0
0.9	0.41	0.51	0.60	0.67	0.74	0.80	1.0
0.7	0.47	0.56	0.66	0.71	0.78	0.83	1.0
0.6	0.53	0.61	0.71	0.76	0.81	0.86	1.0
0.5	0.59	0.67	0.76	0.80	0.84	0.89	1.0
0.4	0.66	0.73	0.81	0.84	0.88	0.91	1.0
0.3	0.74	0.80	0.86	0.88	0.91	0.93	1.0
0.2	0.83	0.87	0.91	0.93	0.95	0.96	1.0
0.1	0.91	0.94	0.96	0.97	0.98	0.99	1.0
0.0	1.00	1.00	1.00	1.00	1.00	1.00	1.0

Source: Created by the Author, the Geometry multiplier provided by White (1987)

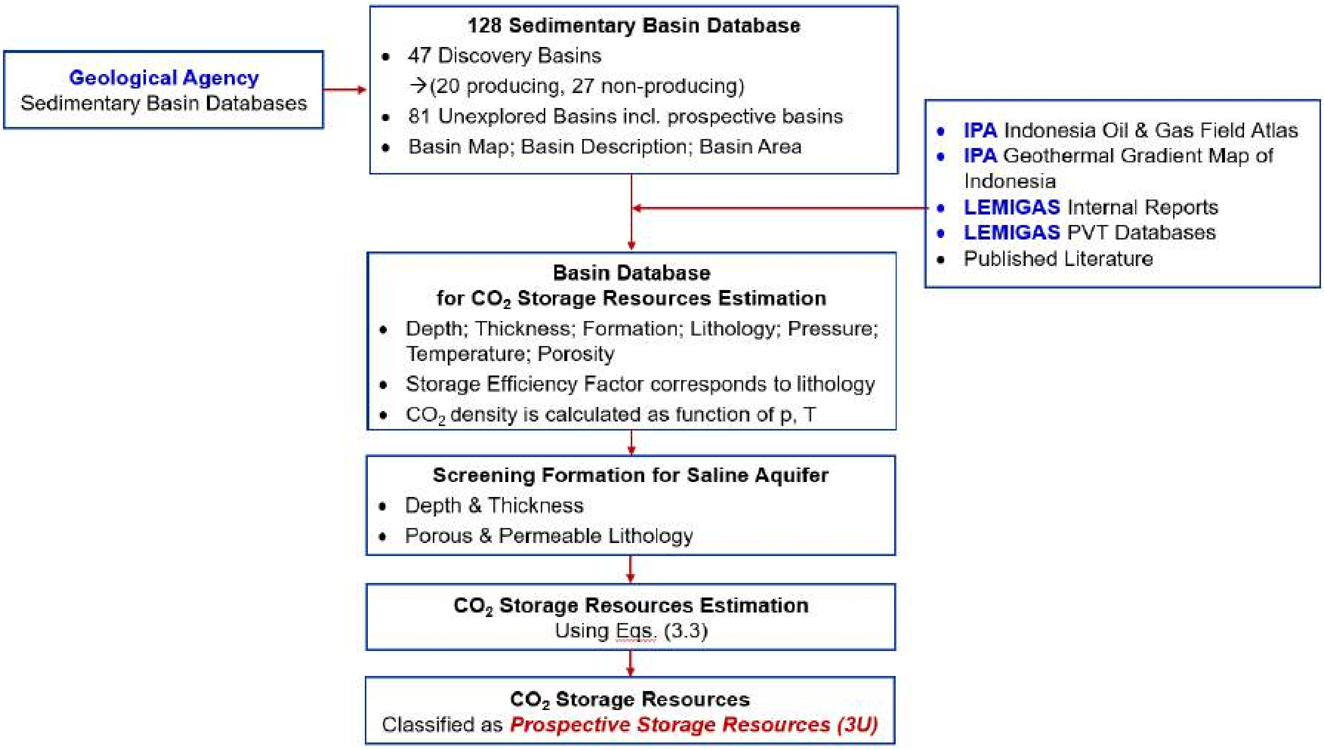
Applying the trap geometry multiplier, G_f, Eq. (3.1) can further be rewritten in the form as,

$$M_{CO_2} = A \times h_g \times G_f \times \phi_{tot} \times \rho_{CO_2} \times E \times C_{fs} \quad (3.3)$$

6) Estimating CO_2 storage of selected saline aquifers in each producing basin using parameters that are already available in the database/table using a volumetric formula of Eq. (3.3). CO_2 density is calculated from the equation of state (Span and Wagner, 1996) accessible on the internet (www.zetaware.com) at specific depth, hydrostatic pressure, and temperature derived from the thermal gradient.

The workflow for basin-scale CO_2 storage resources estimation in saline aquifers is summarised in Figure 3.5.

Figure 3.5. Workflow for CO_2 Storage Resources Estimation in Basin-scale Saline Aquifers



Source: Authors.

5. Estimation of CO_2 Storage in Oil and Gas Fields

CO_2 storage resources estimation is defined on volumetric basis for oil and gas reservoirs based on two primary assumptions: (i) the volume of oil and gas that has or could be produced will become available for CO_2 storage, and (ii) the existing caprock seal will also contain the CO_2 provided the pressure does not increase above the original reservoir pressure before production. No distinction is made in this assessment for the maturity of the field. Because the reservoirs have securely trapped oil and gas within a wide range of depth, no minimum or maximum depth criteria are used for CO_2 storage resources estimates.

The general form of the volumetric-based CO_2 storage resources mass estimate in oil and gas reservoirs is as follows (Goodman et al., 2011; CO2CRC, 2008; CSLF, 2007):

$$M_{CO_2} = \frac{A h_n \phi_e (1-S_{wi})}{B_\alpha} \times RF_{EUR} \times \rho_{CO_2} \qquad (3.4)$$

The product of the area (A), net reservoir thickness (h_n), effective porosity (φ_e), and original hydrocarbon saturation ($1-S_w$) divided by the initial oil or gas formation volume factor (B_α) yields the OOIP or OGIP at standard conditions. RF_{EUR} is the recovery factor at the estimated ultimate recovery (EUR), which represents the expected volume of produced oil and gas and ρ_{CO2} denotes the CO_2 density at reservoir conditions. Produced water and injected are not considered in the estimates.

Estimation of CO_2 storage resources in oil and gas fields are conducted based on reserves databases that reported the OOIP, OGIP, and RF_{EUR} for each field, which is under development or approved for development. The reported OOIP and OGIP are categorised in accordance with the level of certainty associated with the estimates as proved, probable, and possible. Since reserves databases indicated that the OOIP and OGIP at standard conditions have to convert back to reservoir conditions by multiplying with B_o and B_g, the mass CO_2 storage in oil and gas reservoirs is then given by:

$$M_{CO_2} = OOIP \times B_o \times RF_{EUR} \times \rho_{CO_2} \times C_{fo} \quad (3.5)$$

for oil reservoirs, and by:

$$M_{CO_2} = OGIP \times B_g \times RF_{EUR} \times \rho_{CO_2} \times C_{fg} \quad (3.6)$$

for gas reservoirs. Table 3.7 summarises the terms shown in Eqs. (3.5) and (3.6).

Table 3.7. Parameters for CO_2 Storage Resource Estimation in Oil and Gas Reservoirs

Parameter	Unit	Description
M_{CO2}	Mt	Estimate of oil and gas reservoir CO_2 storage resources in million tonnes, Mt.
OOIP	Mstb	Total quantity of crude oil estimated in the reservoir at standard conditions (thousand stock tank barrel, Mstb) before production or original oil in-place
OGIP	MMscf	Total quantity of gas estimated in the reservoir at standard conditions (million standard cubic foot, MMscf) before production or original gas in-place
B_o	bbl/stb	Oil formation volume factor is the volume in barrels occupied in the reservoir at the prevailing pressure and temperature by one stock tank barrel of oil plus its dissolved gas.
B_g	cf/scf	Gas formation volume factor is the volume in cubic foot occupied in the reservoir at the prevailing pressure and temperature by one standard cubic foot of free gas.
RF_{EUR}	fraction	Those quantities of petroleum estimated based on the technical and commercial conditions for the resources, as of a given date, to be potentially recoverable plus those quantities already produced expressed as a fraction of OOIP or OGIP.
ρ_{CO2}	kg/m^3	Density of CO_2 evaluated at the initial pressure and temperature, the same conditions in which the OOIP and OGIP are estimated
C_{fo}	m^3/bbl x Mt/kg	A conversion factor to change the set of units in Eq. (3.5) to million tonnes
C_{fg}	m^3/cf x Mt/kg	A conversion factor to change the set of units in Eq. (3.6) to million tonnes

OGIP = original gas-in-place, OOIP = original oil-in-place.

Source: Authors.

Since the reserves databases only reported the OOIP, OGIP, and RF_{EUR} data, extensive subsurface data from multiple sources including LEMIGAS's PVT databases, GGR study reports, IPA atlas databases, and other published literature have been accessed to collect Bo, Bg, initial reservoir pressure (p), and temperature (T) data required to calculate CO_2 density. The depth for each field is also collected to generate a calibration curve. To fill in missing those parameters for some fields, the following methods are applied (Holloway, 1996):

- Temperature and pressure can be estimated from geothermal and hydrostatic gradients for the basin. If geothermal and hydrostatic gradients are not available, a calibration curve can be drawn for a basin based on initial temperatures and initial pressures of oil and gas fields for which this data exists by plotting this data against depth of the oil and gas field. If no data exists, assume an average gradient of 30°C/km and 10.5 MPa/km.
- The density of CO_2 can easily be calculated from equation of state (Span and Wagner, 1996) accessible on the internet once the temperature and pressure are estimated. For example, for a hydrostatic gradient of 10.5 MPa/km, the density of CO_2 is approximately 740kg/m^3 for a geothermal gradient of 25°C/km, 670 kg/m^3 for 30C°/km, and 600kg/m^3 for 35°C/km at depths greater than 1,000 metres (m).
- In the absence of Bo, a calibration curve is derived for a basin based on pressure and Bo from those oil fields where this data exists and can be used to estimate the values for those oil fields with unknown Bo. If data is not enough to do this, assume a conservative value for Bo of 1.2 bbl/stb.
- In the absence of Bg, a calibration curve is derived for a basin based on pressure and Bg from those gas fields where the data exists, and can be used to estimate the values for those gas fields with unknown Bg. If data is not enough to do this, assume an intermediate Bg of 0.005 cf/scf. For some gas fields, given p, T, and gas compressibility factor, z from the PVT databases, Bg is evaluated by (Guo and Ghalambor, 2005):

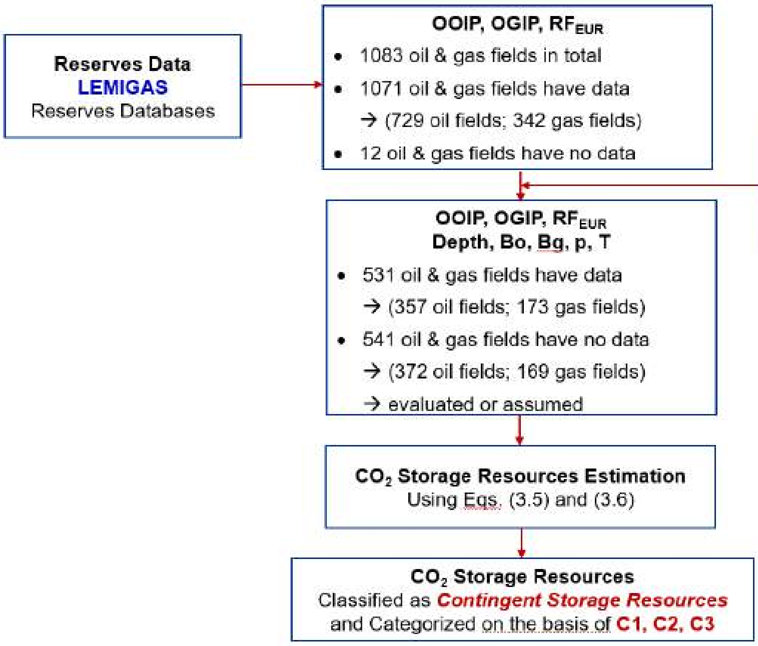
$$B_g = 0.002827\frac{zT}{p} \tag{3.7}$$

- Solution gas and condensate are not considered in estimating CO_2 storage resources because they are implicitly taken into account in the reservoirs through the oil and gas formation volume factors.

The OOIP and OGIP reported in the reserves databases are sufficiently defined with a high level of confidence in the geological and engineering data. Data sources can include 2D and 3D seismic surveys, well log and core data, drill cuttings, biostratigraphy, well test, field production, and fluid data. The RF_{EUR} is derived based on a defined development program, the reliability of input rock properties, reservoir geometry, relative permeability functions, fluid properties, and constraints (e.g. wells, facilities, and commerciality). The estimation may involve production history data to validate the predictive model through history matching, but this is not always the case. As such, the estimated pore volume available for CO_2 storage in oil and gas reservoirs corresponds to the contingent storage resources in the SRMS. The proved, probable, and possible of OOIP and OGIP provided CO_2 storage pore volume corresponds to the terms of C1, C2, and C3 for incremental quantities of contingent storage resources.

The workflow for CO_2 storage resources estimation in oil and gas fields conducted in this study is summarised in Figure 3.6.

Figure 3.6. Workflow for CO_2 Storage Resources Estimation in Oil and Gas Fields



Source: Authors.

6. Development of GIS for Indonesia's CCUS

Geographic Information System (GIS) is an information system designed to work with spatially referenced data or geographic coordinates. A GIS is a database system with special capabilities to handle spatially referenced data, with an operating package work (Barus and Wiradisastra, 2000). The data processed in GIS consists of spatial data and attribute data in digital form. Thus, spatial and attribute analysis can be used. Spatial data is related to spatial location, which is in the form of a map.While attribute data is table data which explains the existence of various objects as spatial data. A GIS is needed because the data or information contained in the GIS is related to geographic locations. Besides, GIS can share information by visualising shapes, sizes, patterns, and impacts. In general, the GIS process consists of three parts or subsystems: data input, data processing and analysis, data presentation (data output). The basic data included in the GIS are obtained from three sources: field data (terrestrial), map data, and remote-sensing data.

The data needed in developing GIS for the CCS study are:

1) *Data input*. This subsystem is tasked with collecting and preparing spatial data and its attributes originating from various official and accountable sources. In this study, spatial data on sedimentary basins came from the Geological Agency of the Ministry of Energy and Mineral Resources, and oil and gas data came from BBPMGB LEMIGAS and SKK Migas. The oil and gas data are then processed to study the potential of CO_2 storage resources in oil and gas fields.
2) *Data manipulation and analysis*. This subsystem determines the information that can be generated by GIS and manipulates and models the data to produce the required information. There are limited sources of spatial data in oil and gas fields. The processing of attribute data is carried out in the Microsoft Excel software and the results inputted as attribute data for the 128 Indonesia sedimentary basins. Likewise, if there is a change in data, the processing results can be inputted to edit and update the data.
3) *Data output*. This subsystem displays or produces the output of all or part of the database in soft and hard copies such as tables, graphs, and maps. The process of creating this subsystem uses the Query-GIS open-source software.

Multiple data sources given in Table 3.1 have been accessed to develop a GIS-based tool for viewing CO_2 storage resources across Indonesia's sedimentary basins. The designed tool allows to display distribution of the CO_2 storage resources by basins and distinguish the category of contingent CO_2 storage resources in hydrocarbon fields of Indonesia's CCUS.

Chapter 4
CO_2 Storage Resources of Indonesia

1. Screening and Ranking of Indonesia's Sedimentary Basins

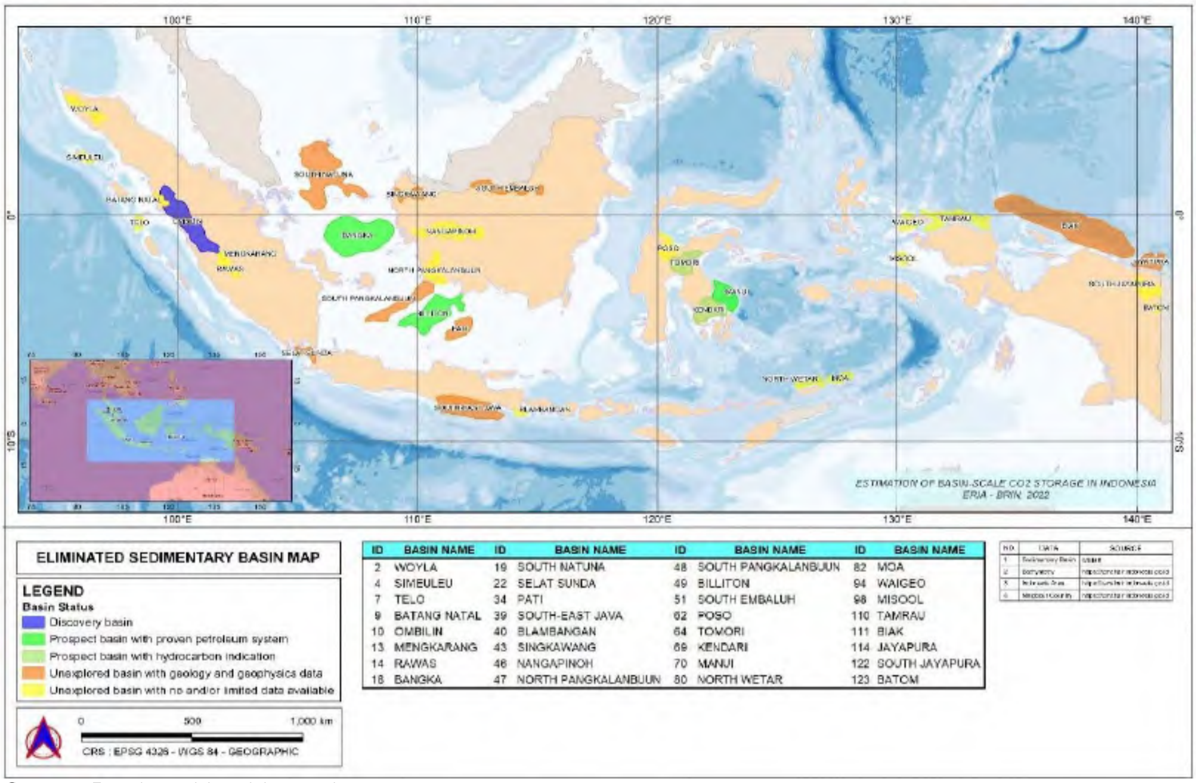
The elimination process is conducted by applying a threshold for the sediment thickness. Hence, the optimum depth for CO_2 storage is the depth that maximises the storage while minimising the cost of well drilling and CO_2 compression and injection into the depth. As suggested in Figure 3.4, the minimum depth for CO_2 storage is 800 m. Any depth less than that will be less efficient. Using this minimum of depth, the elimination process ruled out 32 sedimentary basins. These 32 basins are then excluded from the selection process for quantifying CO_2 storage suitability and ranking process. Table 4.1 presents the 32 eliminated basins. Figure 4.1 shows a GIS map of these 32 eliminated basins, and Figure 4.2 presents sedimentary basin outlines for selected processes.

Table 4.1. Eliminated Basins for CO_2 Storage Suitability Assessment

No.	Basin ID	Basin Name	No.	Basin ID	Basin Name
1	2	Woyla	17	48	South Pangkalanbuun
2	4	Simeuleu	18	49	Billiton
3	7	Telo	19	51	South Embaluh
4	9	Batang Natal	20	62	Poso
5	10	Ombilin	21	64	Tomori
6	13	Mengkarang	22	69	Kendari
7	14	Rawas	23	70	Manui
8	18	Bangka	24	80	North Wetar
9	19	South Natuna	25	82	Moa
10	22	Selat Sunda	26	94	Waigeo
11	34	Pati	27	98	Misool
12	39	Southeast Java	28	110	Tamrau
13	40	Blambangan	29	111	Biak
14	43	Singkawang	30	114	Jayapura
15	46	Nangapinoh	31	122	South Jayapura
16	47	North Pangkalanbuun	32	123	Batom

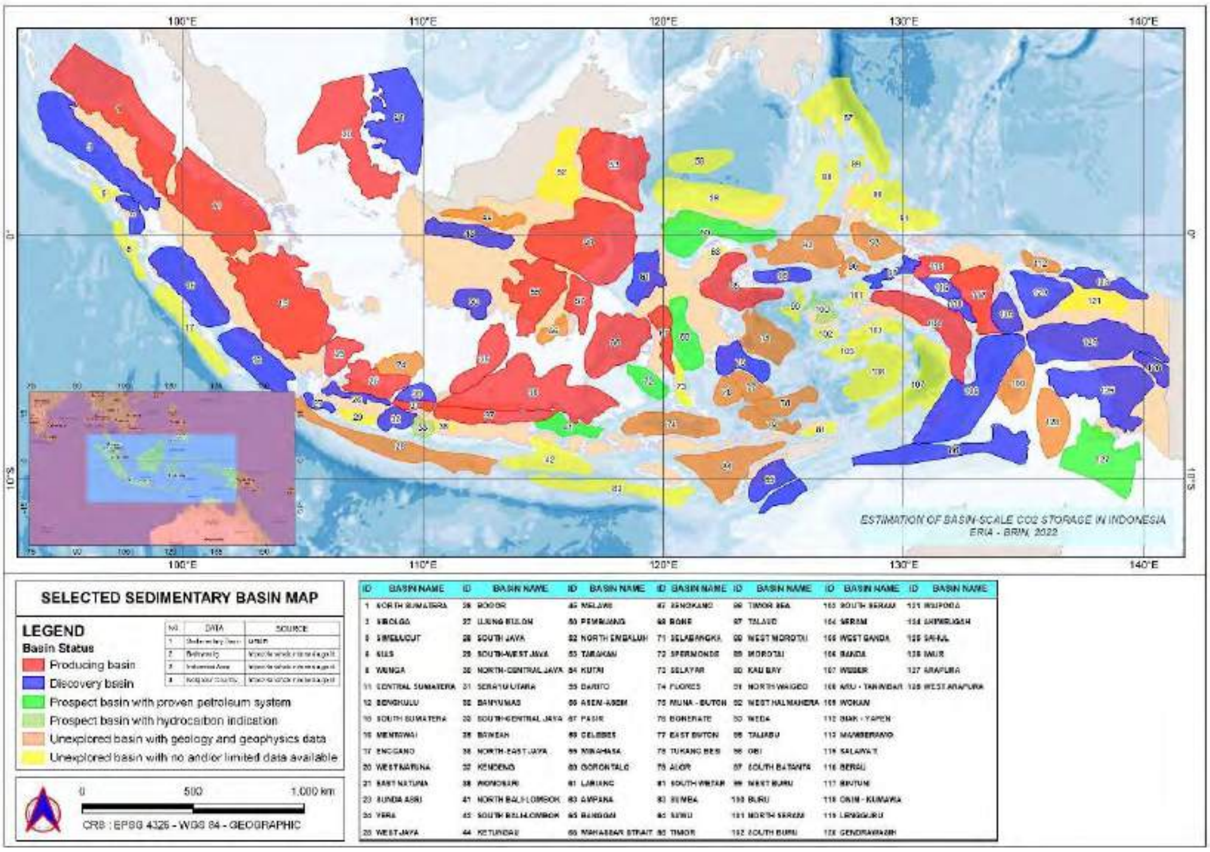
Source: Authors.

Figure 4.1. Map of Eliminated Sedimentary Basins for CO_2 Storage Suitability and Ranking Process



Source Produced by this study.

Figure 4.2. Map of Selected Sedimentary Basins for CO_2 Storage Suitability and Ranking Process



Source: Produced by this study.

The 16 criteria in basin screening have different importance levels from each other. So a weighting factor to each criterion should be applied. The weight values are derived using the pairwise comparison matrix method. This method compares one criterion with another to determine which criterion is more important. The following outlines the steps in deriving the weight of each criterion.

1) Arrange the criteria from the most to the least important. Such arrangement is made based on the experiences and judgment of subject matter experts. The most important criteria ordered by category is as follows: data completeness, storage potential, storage safety, and environmental category.
2) Create a pairwise comparison matrix, which series of column is the serial number, the criteria arranged downwards from the most to least importance, the third column and so on are filled with order of decreasing importance to the right.
3) Compare between criteria, which comparisons of the same criteria are filled zero, while between different criteria are filled with the number reflects the more important/winning criterion.
4) Calculate the number of wins for each criterion.

5) Calculate the weight of each criterion using the formula for the number of more important plus one divided by the total comparison. In this study, 16 criteria lead to the total comparison process of 136.

Table 4.2 presents the pairwise comparison matrix to derive weight values of each criterion.

A quantitative basin ranking process is carried out to rank sedimentary basins in terms of their suitability for CO_2 storage. A table of 96 selected sedimentary basins contains criteria, weight of criteria, and value of classes is generated (Table 4.3). The cumulative score for each basin is obtained by multiplying the class value with the weight of each criterion. The multiplication results for all criteria are then added up to get a score of each sedimentary basins. Table 4.3 also presents the scores of each sedimentary basin. Table 4.4 shows a ranked list of the 96 sedimentary basins.

Table 4.2. Pairwise Comparison Matrix

No.	Criteria	Criteria Number																Weight
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	
1	Basin maturity	0																0.1176
2	Basin size (sq.km.)	1	0															0.1103
3	Reservoirs porosity (%)	1	2	0														0.1029
4	Reservoir thickness (m)	1	2	3	0													0.0956
5	Sediment thickness (m)	1	2	3	4	0												0.0882
6	Reservoir temperature (ºC)	1	2	3	4	5	0											0.0809
7	Gradient geothermal ºC/km	1	2	3	4	5	6	0										0.0735
8	Seal	1	2	3	4	5	6	7	0									0.0662
9	Tectonic setting	1	2	3	4	5	6	7	8	0								0.0588
10	Seismicity max. (pga)	1	2	3	4	5	6	7	8	9	0							0.0515
11	Earthquake magnitude (MMI)	1	2	3	4	5	6	7	8	9	10	0						0.0441
12	Volcanism (km. distance)	1	2	3	4	5	6	7	8	9	10	11	0					0.0368
13	Fault & fracture intensity	1	2	3	4	5	6	7	8	9	10	11	12	0				0.0294
14	Trap development	1	2	3	4	5	6	7	8	9	10	11	12	13	0			0.0221
15	Basin location/water depth	1	2	3	4	5	6	7	8	9	10	11	12	13	14	0		0.0147
16	Hydrology	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	0	0.0074
Win/More Important		15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0	
Count/Amount		16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	1.0000
TOTAL COUNT/AMOUNT		136																

Source: Produced by this study.

Table 4.3. Basin Scoring for CO_2 Storage Suitability

ID	Basin	Criteria and Class																Score
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	
1	North Sumatra	5	5	5	4	5	2	2	2	4	2	3	5	3	4	3	5	3.8309
3	Sibolga	4	3	4	1	3	4	4	2	3	1	2	4	3	4	3	3	3.0294
5	Simelucut	1	1	1	1	2	5	4	1	1	1	3	1	4	3	2	1	1.8676
6	Nias	4	1	1	1	3	5	5	1	1	1	1	4	4	3	3	2	2.4265
8	Wunga	1	1	1	1	2	4	1	1	1	1	3	1	4	4	1	1	1.5735
11	Centra Sumatra	5	4	5	5	3	3	1	2	4	3	3	4	3	4	4	3	3.6618
12	Bengkulu	4	2	1	1	2	3	4	3	3	1	1	3	3	1	3	3	2.3603
15	South Sumatra	5	5	5	4	4	2	2	4	4	3	3	5	3	4	5	4	3.9485
16	Mentawai	4	3	5	1	3	3	2	2	2	1	1	1	3	3	3	2	2.6618
17	Enggano	1	1	1	1	2	3	2	1	1	1	3	1	4	4	1	1	1.5662
20	West Natuna	5	4	5	4	5	2	3	4	5	5	5	3	5	5	2	1	4.1912
21	East Natuna	4	3	4	4	5	1	2	3	5	5	5	3	5	4	3	2	3.6397
23	Sunda Asri	5	1	4	2	4	3	2	3	4	4	4	3	3	3	4	1	3.1912
24	Vera	3	1	4	1	2	3	3	2	4	5	5	3	4	4	4	1	2.8382
25	West Java	5	2	4	4	3	3	2	5	4	4	5	4	4	4	4	3	3.6838
26	Bogor	4	1	3	3	4	1	2	1	4	3	3	1	1	4	5	4	2.6029
27	Ujung Kulon	4	1	3	3	2	1	1	2	3	2	2	3	3	4	3	3	2.3603
28	South Java	3	3	1	1	5	2	1	1	1	3	3	1	4	3	1	1	2.2132
29	Southwest Java	1	1	1	1	2	1	3	1	3	3	3	1	2	3	3	3	1.6618

ID	Basin	Criteria and Class																Score
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	
30	North-central Java	4	1	5	1	3	5	2	2	4	5	5	3	4	4	4	1	3.2353
31	North Serayu	5	1	1	1	3	4	2	1	4	4	3	1	2	4	4	3	2.5368
32	Banyumas	4	1	1	1	2	3	2	1	3	3	3	3	1	4	3	5	2.1838
33	South-Central Java	3	1	4	1	2	5	4	1	3	3	3	3	2	5	3	5	2.7353
35	Bawean	5	2	1	1	2	3	2	1	4	5	4	1	4	4	4	1	2.6176
36	Northeast Java	5	5	5	4	3	3	3	4	4	5	3	4	4	4	3	3	4.0735
37	Kendeng	5	2	5	4	3	3	3	4	2	4	4	4	2	4	3	5	3.5735
38	Wonosari	1	1	1	1	2	5	3	1	3	4	3	1	2	4	5	3	2.0882
41	North Bali-Lombok	3	1	1	1	4	1	3	1	4	1	1	1	2	3	1	1	1.8971
42	South Bali-Lombok	1	2	1	1	2	3	3	1	1	3	3	1	3	4	3	1	1.8529
44	Ketungau	3	1	4	1	3	3	2	1	4	5	5	4	5	3	5	4	2.8676
45	Melawi	3	1	4	1	3	3	3	2	4	5	5	4	5	3	5	3	3.0000
50	Pembuang	4	1	1	1	2	4	3	1	4	5	5	3	5	4	4	4	2.7132
52	North Embaluh	1	2	1	1	4	3	3	1	1	5	5	3	5	4	5	2	2.3897
53	Tarakan	5	3	4	4	5	1	3	5	4	4	2	4	4	4	3	3	3.7353
54	Kutai	5	5	5	4	5	3	3	5	4	4	3	5	4	3	3	4	4.2868
55	Barito	5	3	4	5	4	3	3	3	4	5	4	3	5	4	4	4	3.9265
56	Asem-asem	3	1	1	1	3	3	3	1	4	5	4	3	5	4	4	3	2.5515
57	Pasir	5	1	5	4	2	3	3	2	4	5	4	4	5	4	3	3	3.4853

ID	Basin	Criteria and Class																Score
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	
58	Celebes	1	1	1	1	5	3	3	1	1	3	3	1	4	3	1	1	1.9853
59	Minahasa	1	3	1	1	5	3	1	1	1	1	2	1	2	4	3	3	1.9191
60	Gorontalo	3	2	1	1	5	4	3	1	4	2	2	4	1	4	3	1	2.5662
61	Lariang	4	1	4	4	2	4	4	1	4	2	3	4	4	3	3	3	3.1029
63	Ampana	1	1	1	1	2	4	3	1	3	3	3	1	3	4	3	1	1.9412
65	Banggai	5	2	4	5	5	3	4	1	5	3	2	4	4	3	3	3	3.6765
66	Makassar Strait	4	3	4	3	5	3	4	2	3	2	2	3	5	3	3	1	3.3529
67	Sengkang	5	1	5	5	3	3	5	1	4	5	2	4	5	4	5	4	3.6324
68	Bone	3	2	5	5	5	3	4	1	4	1	4	4	5	2	3	1	3.4632
71	Selabangka	3	2	1	1	4	3	4	1	2	4	4	1	4	3	1	1	2.4706
72	Spermonde	3	1	1	1	2	3	4	1	4	5	4	4	4	3	3	1	2.4926
73	Selayar	1	1	1	1	3	3	4	1	4	5	4	1	4	4	3	1	2.2574
74	Flores	3	2	1	1	4	3	4	1	4	1	1	1	3	4	3	1	2.3235
75	Muna-Buton	4	1	1	1	2	3	5	1	5	5	4	4	4	4	3	3	2.7794
76	Bonerate	3	1	1	1	2	3	4	1	5	5	4	1	4	4	2	1	2.4485
77	East Buton	3	1	3	1	3	3	4	1	5	5	4	1	3	4	1	1	2.6985
78	Tukang Besi	3	1	1	1	3	3	4	1	5	4	3	1	1	4	1	1	2.3382
79	Alor	3	1	1	1	3	3	4	1	4	1	2	1	1	4	1	1	2.0809
81	South Wetar	1	1	1	1	2	4	4	1	1	3	2	1	3	4	2	1	1.8382
83	Sumba	1	2	1	1	2	3	4	1	1	1	4	1	4	3	1	1	1.8456
84	Sawu	3	2	1	1	4	4	4	1	1	3	3	1	2	4	1	1	2.3603
85	Timor	4	1	3	5	2	5	4	1	3	3	3	3	4	4	3	3	3.1544
86	Timor Sea	4	3	3	4	3	5	4	1	5	4	3	3	5	4	1	1	3.5221

ID	Basin	Criteria and Class																Score
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	
87	Talaud	1	3	1	1	2	5	4	1	1	1	3	1	4	3	1	1	2.0735
88	West Morotai	1	1	1	1	3	5	4	1	2	2	4	1	3	4	1	1	2.0882
89	Morotai	1	1	1	1	3	5	4	1	2	1	3	1	4	3	1	1	2.0000
90	Teluk Kau	1	1	1	1	4	5	3	1	1	1	2	1	2	4	3	3	1.9191
91	North Waigeo	1	1	1	1	3	4	3	1	1	3	3	1	4	2	2	1	1.8824
92	West Halmahera	3	2	1	1	3	4	3	1	2	3	3	1	3	4	2	1	2.3015
93	Weda	3	1	1	1	4	5	3	1	2	4	3	1	3	4	2	1	2.4118
95	Taliabu	4	1	1	1	2	4	4	1	5	1	1	1	5	4	3	2	2.3603
96	Obi	3	1	1	1	2	5	3	1	2	2	3	1	4	3	3	1	2.1544
97	South Batanta	4	1	1	1	3	5	3	1	5	1	3	1	5	3	2	1	2.5000
99	Buru Barat	3	1	1	1	3	4	3	1	3	3	4	1	5	4	1	1	2.3382
100	Buru	3	1	1	1	2	5	3	1	3	3	3	1	5	4	3	2	2.3235
101	North Seram	1	1	1	1	3	5	3	1	3	3	3	1	5	1	1	1	2.0735
102	South Buru	3	1	1	1	3	5	3	1	2	4	3	1	5	4	1	1	2.3676
103	South Seram	1	1	1	1	3	5	3	1	3	4	1	1	3	4	2	1	2.0588
104	Seram	5	3	2	5	4	3	3	3	3	1	2	4	4	4	3	3	3.3529
105	West Banda	1	1	1	1	2	5	4	1	2	4	3	1	4	4	1	1	2.0882
106	Banda	1	2	1	1	3	5	3	1	2	3	3	1	2	4	1	1	2.1029
107	Weber	1	2	1	1	4	4	3	1	2	2	3	1	3	4	1	1	2.0882
108	Aru-Tanimbar	4	4	4	5	2	3	1	1	3	2	3	3	4	4	3	3	3.1544

ID	Basin	Criteria and Class																Score
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	
109	Wokam	3	2	1	1	3	3	2	1	5	3	3	1	5	4	4	3	2.4265
112	Biak-Yapen	3	1	1	1	2	3	3	1	1	3	1	1	5	4	3	3	1.9632
113	Mamberamo	4	1	5	5	2	3	3	1	1	1	1	3	5	3	3	3	2.8235
115	Salawati	5	1	4	3	2	3	2	2	4	4	3	4	5	4	4	3	3.1324
116	Berau	4	1	1	1	3	3	3	1	4	5	3	4	5	3	4	1	2.6250
117	Bintuni	5	2	2	5	3	3	3	3	4	3	3	4	5	3	4	3	3.3824
118	Onin-Kumawa	4	1	1	1	2	3	3	1	4	5	4	1	5	4	4	3	2.5074
119	Lengguru	4	1	1	1	3	3	3	1	4	1	3	1	5	4	5	3	2.3603
120	Cendrawasih	4	2	4	3	4	3	3	1	1	1	1	4	5	4	2	3	2.8603
121	Waipoga	1	1	1	1	3	3	2	1	1	2	3	1	5	4	5	4	1.8162
124	Akimeugah	4	4	1	1	5	3	4	1	4	2	1	3	5	4	4	4	2.9706
125	Sahul	4	3	1	1	3	3	2	1	4	4	3	5	5	4	4	3	2.7941
126	Iwur	4	1	2	3	5	4	2	1	4	3	1	4	5	4	5	3	2.9632
127	Arafura	3	3	1	5	2	4	3	1	5	5	5	3	5	4	4	1	3.2353
128	West Arafura	3	2	5	5	2	3	2	1	5	5	4	3	5	4	4	1	3.3382
WEIGHT		0.1176	0.1103	0.1029	0.0956	0.0882	0.0809	0.0735	0.0662	0.0588	0.0515	0.0441	0.0368	0.0294	0.0221	0.0147	0.0074	

Source: Produced by this study.

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Table 4.4. Ranking of Indonesia's Sedimentary Basins for CO_2 Storage Suitability

Ranking	Basin Name	Basin ID	Score	Basin Statues
1	Kutai	54	4.287	Producing Basin
2	West Natuna	20	4.191	Producing Basin
3	Northeast Java	36	4.074	Producing Basin
4	South Sumatra	15	3.949	Producing Basin
5	Barito	55	3.926	Producing Basin
6	North Sumatra	1	3.831	Producing Basin
7	Tarakan	53	3.735	Producing Basin
8	West Java	25	3.684	Producing Basin
9	Banggai	65	3.676	Producing Basin
10	Central Sumatra	11	3.662	Producing Basin
11	East Natuna	21	3.640	Producing Basin
12	Sengkang	67	3.632	Discovery Basin
13	Kendeng	37	3.574	Producing Basin
14	Timor Sea	86	3.522	Discovery Basin
15	Pasir	57	3.485	Producing Basin
16	Bone	68	3.463	Prospect Basin with Proven Petroleum System
17	Bintuni	117	3.382	Producing Basin
18	Makassar Strait	66	3.353	Producing Basin
19	Seram	104	3.353	Producing Basin
20	West Arafura	128	3.338	Basin with Geology and Geophysics Data
21	Arafura	127	3.235	Prospect Basin with Proven Petroleum System
22	North-Central Java	30	3.235	Discovery Basin
23	Sunda Asri	23	3.191	Producing Basin
24	Aru – Tanimbar	108	3.154	Discovery Basin
25	Timor	85	3.154	Discovery Basin
26	Salawati	115	3.132	Producing Basin
27	Lariang	61	3.103	Discovery Basin
28	Sibolga	3	3.029	Discovery Basin
29	Melawi	45	3.000	Discovery Basin
30	Akimeugah	124	2.971	Discovery Basin
31	Iwur	126	2.963	Discovery Basin

Ranking	Basin Name	Basin ID	Score	Basin Statues
32	Ketungau	44	2.868	Basin with Geology and Geophysics Data
33	Cendrawasih	120	2.860	Discovery Basin
34	Vera	24	2.838	Basin with Geology and Geophysics Data
35	Mamberamo	113	2.824	Discovery Basin
36	Sahul	125	2.794	Discovery Basin
37	Muna – Buton	75	2.779	Discovery Basin
38	South-Central Java	33	2.735	Basin with Hydrocarbon Indication
39	East Buton	77	2.699	Discovery Basin
40	Pembuang	50	2.647	Basin with Geology and Geophysics Data
41	Berau	116	2.625	Discovery Basin
42	Mentawai	16	2.625	Discovery Basin
43	Bawean	35	2.618	Producing Basin
44	Bogor	26	2.603	Discovery Basin
45	Gorontalo	60	2.566	Prospect Basin with Proven Petroleum System
46	Asem-asem	56	2.551	Basin with Geology and Geophysics Data
47	North Serayu	31	2.537	Producing Basin
48	Onin - Kumawa	118	2.507	Discovery Basin
49	South Batanta	97	2.500	Discovery Basin
50	Spermonde	72	2.493	Prospect Basin with Proven Petroleum System
51	Selabangka	71	2.471	Basin with Geology and Geophysics Data
52	Bonerate	76	2.449	Basin with Geology and Geophysics Data
53	Wokam	109	2.426	Basin with Geology and Geophysics Data
54	Nias	6	2.426	Discovery Basin
55	Weda	93	2.412	Basin with Geology and Geophysics Data
56	North Embaluh	52	2.390	Basin with No/Limited Data Availability
57	South Buru	102	2.368	Basin with Hydrocarbon Indication
58	Ujung Kulon	27	2.360	Discovery Basin
59	Sawu	84	2.360	Basin with Geology and Geophysics Data
60	Bengkulu	12	2.360	Discovery Basin
61	Taliabu	95	2.360	Discovery Basin
62	Lengguru	119	2.360	Discovery Basin
63	West Buru	99	2.338	Basin with Hydrocarbon Indication
64	Tukang Besi	78	2.338	Basin with Geology and Geophysics Data

Ranking	Basin Name	Basin ID	Score	Basin Statues
65	Flores	74	2.324	Basin with Geology and Geophysics Data
66	Buru	100	2.324	Basin with Hydrocarbon Indication
67	West Halmahera	92	2.301	Basin with Geology and Geophysics Data
68	Selayar	73	2.257	Basin with No/Limited Data Availability
69	South Java	28	2.213	Basin with Geology and Geophysics Data
70	Banyumas	32	2.184	Discovery Basin
71	Obi	96	2.154	Basin with Geology and Geophysics Data
72	Banda	106	2.103	Basin with No/Limited Data Availability
73	West Morotai	88	2.088	Basin with No/Limited Data Availability
74	Wonosari	38	2.088	Basin with No/Limited Data Availability
75	West Banda	105	2.088	Basin with No/Limited Data Availability
76	Weber	107	2.088	Basin with No/Limited Data Availability
77	Alor	79	2.081	Basin with Geology and Geophysics Data
78	Talaud	87	2.074	Basin with No/Limited Data Availability
79	North Seram	101	2.074	Basin with No/Limited Data Availability
80	South Seram	103	2.059	Basin with No/Limited Data Availability
81	Morotai	89	2.000	Basin with No/Limited Data Availability
82	Celebes	58	1.985	Basin with No/Limited Data Availability
83	Biak – Yapen	112	1.963	Basin with Geology and Geophysics Data
84	Ampana	63	1.941	Basin with No/Limited Data Availability
85	Minahasa	59	1.919	Basin with No/Limited Data Availability
86	Teluk Kau	90	1.919	Basin with No/Limited Data Availability
87	North Bali-Lombok	41	1.897	Prospect Basin with Proven Petroleum System
88	North Waigeo	91	1.882	Basin with No/Limited Data Availability
89	Simelucut	5	1.868	Basin with No/Limited Data Availability
90	South Bali-Lombok	42	1.853	Basin with Hydrocarbon Indication
91	Sumba	83	1.846	Basin with No/Limited Data Availability
92	South Wetar	81	1.838	Basin with No/Limited Data Availability
93	Waipoga	121	1.816	Basin with No/Limited Data Availability
94	Southwest Java	29	1.662	Basin with No/Limited Data Availability
95	Wunga	8	1.574	Basin with No/Limited Data Availability
96	Enggano	17	1.566	Basin with No/Limited Data Availability

Source: Produced by this study.

The top 20 basins are dominated by oil- and gas-producing basins, followed by discovery status and proven petroleum systems. This sequence is supported by the weighting of the maturity criteria for productive basins which rank highest, followed by the size of the sedimentary basins. The average area of this first group of basins is more than 50 square kilometre (km^2). The West Java Basin with an area of 30 km^2 is included in this group because this basin has well-characterised reservoirs, leading to higher data intensity for all criteria. The Bone and Arafura Barat basins are supported by basin area and reservoir data.

The second group of 20 basins in order (21st to the 40th) is mainly occupied by basins with status basin discoveries, followed by basins with indications, and basins with proven petroleum systems.

The third sedimentary basin group (41st to 96th) is dominantly occupied by sedimentary basins with status with no/limited data availability, with geology and geophysics data and little discovery. In general, this group of basins is still very limited in oil and gas exploration activities, leading to minimum geological data to support the basin-scale assessment.

2. CO_2 Storage Resources in Deep Saline Aquifers

Of 96 basins that passed the elimination stage, 21 basins have adequate data for CO_2 storage resources estimation. The CO_2 storage resources for these 21 basins are given in Table 4.5. CO_2 storage resources are estimated to 680.57 Gt in deep saline aquifers and classified as prospective storage resources (3U). There are 19 producing basins and 2 discovery basins. Most of them are home of mature oil and gas fields, leading to having adequate data for CO_2 storage resources estimation.

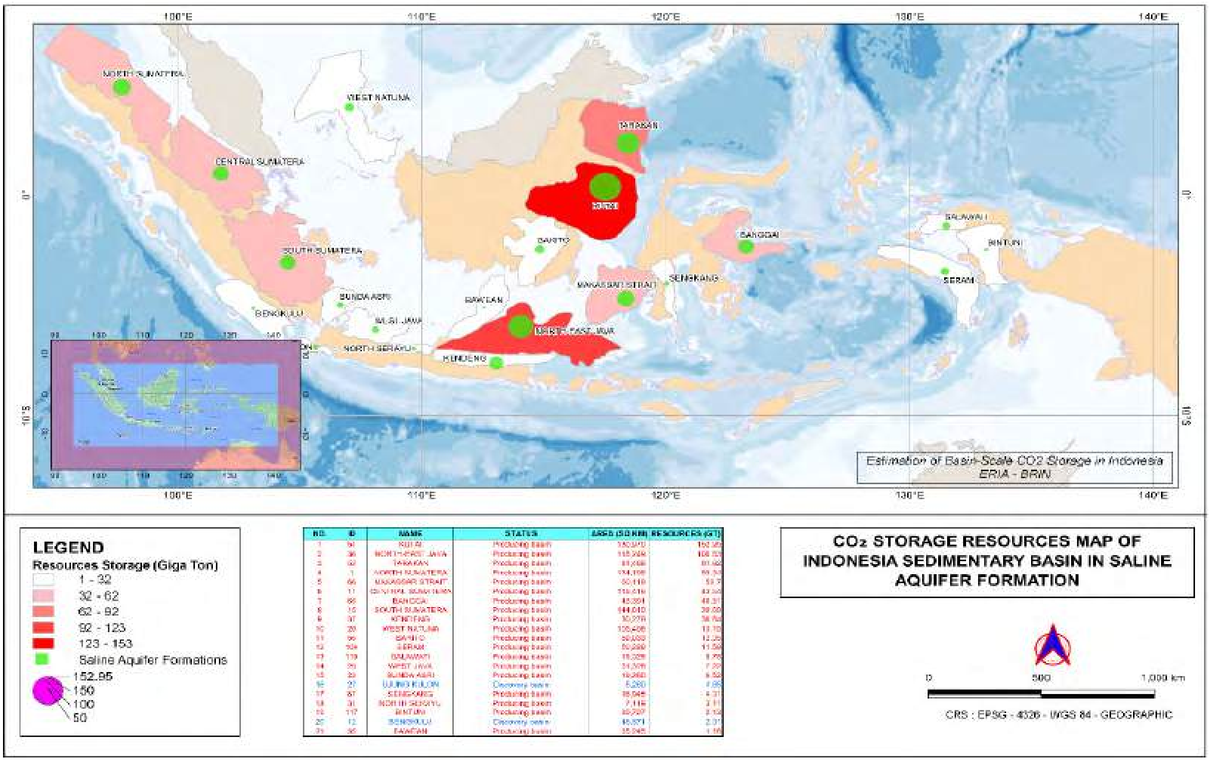
Table 4.5. CO_2 Storage Resources Estimation in Deep Saline Aquifers by Basin Sorted from Largest to Smallest

NO	BASIN ID	BASIN NAME	BASIN STATUS	FORMATION	LITHOLOGY	CO_2 STORAGE RESOURCES		
						Kg	Gigaton (Gt)	
1	54	KUTAI	Producing basin	Balikpapan	Sandstone	1.5295E+14	152.95	152.95
2	36	NORTHEAST JAVA	Producing basin	Ngrayong	Sandstone	1.0083E+14	100.83	100.83
3	53	TARAKAN	Producing basin	Tarakan Fm	Sandstone	9.1920E+13	91.92	91.92
4	1	NORTH SUMATERA	Producing basin	Baong	Sandstone	4.2654E+13	42.65	53.34
				Keutapang	Sandstone	1.0683E+13	10.68	
5	66	MAKASSAR STRAIT	Producing basin	Lower Tanjung	Sandstone	2.5657E+13	25.66	50.70
				Berai	Limestone	2.5041E+13	25.04	
6	11	CENTRAL SUMATERA	Producing basin	Menggala	Sandstone	2.8296E+13	28.30	43.54
				Bekasap	Sandstone	1.5246E+13	15.25	
7	65	BANGGAI	Producing basin	Minahaki	Limestone	3.2400E+13	32.40	40.31
				Tomori	Limestone	7.9079E+12	7.91	
8	15	SOUTH SUMATERA	Producing basin	Talang Akar	sandstone	2.4633E+13	24.63	39.69
				Baturaja	carbonate	1.5054E+13	15.05	
9	37	KENDENG	Producing basin	Ngimbang	Sandstone	2.1133E+12	2.11	30.64
				Kujung	Limestone	2.5268E+13	25.27	
				Rancak	Limestone	3.2602E+12	3.26	
10	20	WEST NATUNA	Producing basin	Lower Gabus	Sandstone	1.3152E+13	13.15	13.15
11	55	BARITO	Producing basin	Lower Tanjung Fm	Sandstone	1.2052E+13	12.05	12.05
12	104	SERAM	Producing basin	Manusela Fm	Limestone	1.1581E+13	11.58	11.58
13	115	SALAWATI	Producing basin	Kais	Limestone	8.7547E+12	8.75	8.75
14	25	WEST JAVA	Producing basin	Upper Cibulakan	sandstone	5.0705E+12	5.07	7.22
				Baturaja	carbonate	2.1540E+12	2.15	
15	23	SUNDA ASRI	Producing basin	Baturaja	Limestone	2.7382E+12	2.74	6.52
				Talangakar	Sandstone	3.7864E+12	3.79	
16	27	UJUNG KULON	Discovery basin	Rajamandala	Sandstone	4.6466E+12	4.65	4.65
17	67	SENGKANG	Producing basin	Tacipi	Limestone	4.3091E+12	4.31	4.31
18	31	NORTH SERAYU	Producing basin	Halang Fm	Sandstone	3.1101E+12	3.11	3.11
19	117	BINTUNI	Producing basin	L.Kambelangan	Sandstone	2.1323E+12	2.13	2.13
20	12	BENGKULU	Discovery basin	Lemau Fm	Limestone	2.0138E+12	2.01	2.01
21	35	BAWEAN	Producing basin	Kujung	Limestone	1.1609E+12	1.16	1.16
			Total CO_2 Storage Resources			**6.8057E+14**	**680.57**	**680.57**

Source: Produced by this study.

The top three highest CO_2 storage resources are Kutai, Northeast Java, and Tarakan basins. Kutai Basin shows significant CO_2 storage resources of 152.95 Gt because it has very good reservoir, thick and spread wide within Balikpapan formation. CO_2 storage resources in Northeast Java most likely distributed across Ngaryong formation have remarkable area and reservoir thick with good porosity. Among several formations in Tarakan basin, the Tarakan sandstone formation has a larger and thicker area which leads to the big CO_2 storage resources of 91.92 Gt. Bawean Basin, on the other hand, has the smallest CO_2 storage resource of 1.16 Gt because of its thinnest reservoir. Figure 4.3 shows a GIS map for CO_2 storage resources of Indonesia's sedimentary basins in saline aquifer. The green circle radius reflects the size of CO_2 storage resources.

Figure 4.3. Distribution of CO_2 Storage Resources in Assessed Deep Saline Aquifers across Indonesia's Sedimentary Basins



Source: Produced by this study.

Table 4.6 summarises the characteristics and properties of the 21 sedimentary basins assessed for CO_2 storage resources estimation in saline aquifers. Several essential details include basin identity, hydrocarbon indication, tectonic setting, size, geothermal gradient, and geological storage system elements consisting of reservoir and seal properties. Multiple data sources have been accessed to develop this data set. More detailed descriptions of each basin are given in Appendix B.

Table 4.6. Sedimentary Basins with Adequate Data for Estimating CO_2 Storage Resources in Saline Aquifers

No	No. (Basin ID)	Basin Name	Basin Status	HC Indication	Tectonic Setting	Basement Type	Geometric Factor	Area (size) (km2)	Average Geothermal Gradient (°C/100m)	Storage System Elements: Reservoir Rock (play): Formation name	Lithology	Top Formation Depth (Avg) (m)	Thickness (m) range	Thickness (m) average	Porosity range	Porosity average	Permeability	Age	Seal Rocks: Formation name	Lithology	Age
1	1	North Sumatra	Producing basin	255 gas well	Rifting Valley Back Arc	granitic, meta sediment, continent of sundaland	68.9	134,196	4.8	Formasi Arun	Limestone/Carbonate	2,896.0	335 m	335 m	16%	16.2%	1-1466 mD	Lower Miocene	Formasi Baong	Shale	Middle Miocene
				1938 oil well						Formasi Baong	Sandstone	1,326.0	35 - 500 m	297 m	18.5 - 21 %	19.8%	4-1500 mD	Middle Miocene			
2	11	Central Sumatra	Producing basin	77 gas wells	Rifting Valley Back Arc	granitic, meta sediment, continent of sundaland	68.1	115,416	6.44	Menggala Fm	Sandstone	988.0	21.8 - 845 m	311 m	17 - 35 %	23%		Early Miocene	Telisa Fm	Shale	Middle Miocene
				13134 oil wells						Bekasap Fm	Sandstone	768.0	7.6 - 865 m	237 m	17 - 35 %	25%		Early Miocene			
				50 result unreported						Lower Red Bed Fm	Sandstone				15% - 20%	18%		Oligocene			
3	12	Bengkulu	Discovery basin	2 wells with oil shows	Rifting Valley Fore Arc	granitic, meta sediment, continent of sundaland	75.5	48,571	2.99	Parigi Fm	Limestone	1,125.0		185 m		3.7%		Middle Miocene	Muara Enim Fm	Shale	Late Miocene
				5 dry wells						Baturaja Fm	Limestone							Early Miocene	Gumai Fm	Shale	Early-Middle Miocene
										Talangakar Fm	Sandstone							Late Oligocene			
4	15	South Sumatra	Producing basin	320 gas wells	Rifting Valley Back Arc	granitic, meta sediment, continent of sundaland	68.0	144,619	4.99	Air Benakat Fm	Sandstone	372.0	45 - 1005 m	356 m	18 - 28 %	24%	10 - 3200 mD	Middle Miocene	Muara Enim Fm	Shale	Late Miocene
				2794 oil wells						Baturaja Fm	Limestone	1,170.0	53 - 264 m	159 m	16 - 25 %	21%	100 - 3600 mD	Early Miocene	Gumai Fm	Shale	Early-Middle Miocene
				163 unreported wells						Talangakar Fm	Sandstone	1,300.0	31 - 249 m	140 m	17 - 25 %	21%	203 - 500 mD	Late Oligocene			
5	20	West Natuna	Producing basin	113 gas wells	Rifting Valley Passive Margin	granitic, meta sediment, continent of sundaland	68.0	105,456	3.92	Lower Arang Fm	Sandstone				12% - 26%	19%		Early Miocene	Arang Fm	Shale	Early-Middle Miocene
				203 oil wells						Upper Gabus Fm	Sandstone				23% - 28%	26%		Late Oligocene	Barat Fm	Shale	Late Oligocene
				6 unreported wells						Lower Gabus Fm	Sandstone	1,653.4	34 - 177 m	90 m	21 - 25 %	23%	180 - 2500 mD	Early Oligocene	Benua Fm	Shale	Early Oligocene
6	23	Sunda Asri	Producing basin	35 gas wells	Rifting Valley Back Arc	granitic, meta sediment, continent of sundaland	68.0	19,260	4.49	Baturaja Fm	Limestone	900.0	28 - 667 m	197 m	21 - 26 %	24.6%	52 - 9300 mD	Early Miocene	Gumai Fm	Shale	Miocene
				1183 oil wells						Talangakar Fm	Sandstone	1,449.0	55 - 213 m	123 m	24 - 31 %	27%	50 - 10500 mD	Late Oligocene			
				40 unreported wells						Banuwati Fm	Sandstone				5 - 15%	10%		Eocene - E Oligocene	Banuwati Fm	Shale	Eocene - E Oligocene
7	25	West Java	Producing basin	207 gas wells	Rifting Valley Back Arc	granitic, meta sediment, continent of sundaland	68.2	31,326	4.54	Parigi Fm	Limestone	780.0	84 m	84 m	15 %	15%		Late Miocene	Cisubuh Fm	Shale	Pliocene
				853 oil wells						Upper Cibulakan Fm	Sandstone	833.0	16 - 453 m	200 m	22 - 44 %	30%	9 - 3150 mD	Middle Miocene	Upper Cibulakan	Shale	Middle Miocene
				398 oil and gas wells						Baturaja Fm	Limestone	896.0		125 m	23 %	23%	1500 mD	Early Miocene	Upper Cibulakan	Shale	Middle Miocene
				48 unreported wells						Jatibarang Fm	Vulcaniclastic	2,063.0	29 - 355 m	192 m	18 - 20 %	19%		Eocene-Oligocene			
8	27	Ujung Kulon	Discovery basin	1 well with oil and gas show	Rifting Valley Intermontane Basin	granitic, meta sediment, continent of sundaland	70.1	5,260	5.56	Rajamandala Fm	Sandstone		800 - 2200 m		10 - 20%	15%		Oligocene	Batuasih Fm	Shale	Miocene
9	31	North Serayu	Producing basin	13 oil wells, 3 gas wells	Rifting Valley Back Arc	granitic, meta sediment, continent of sundaland	70.0	7,119		Halang Fm	Sandstone	800 m		632 m		20%		Late Miocene	Kalibiuk Fm	Shale	Pliocene
10	35	Bawean	Producing basin	21 gas wells, 5 wells with gas shows	Rifting Valley Back Arc	granitic, meta sediment, continent of sundaland	69.5	35,245	4.6	Tuban/Tawun	Sandstone	640.0		125 m		30%		Middle Miocene	Mundu Fm	Shale	Pliocene
										Kujung Fm	Limestone	723.0		106 m		20%		Oligo-Miocene	Tawun	Shale	Middfle Mioce
11	36	Northeast Java	Producing basin	1006 oil wells	Rifting Valley Back Arc	granitic, meta sediment, continent of sundaland	68.8	118,249	3.89	Paciran Fm	Limestone							Pliocene	Mundu Fm	Shale	Pliocene
				72 gas wells						Bulu Fm	Limestone				12 - 15%	14%		Late Miocene			
				34 unreported wells						Ngrayong	Sandstone	987.8	252 - 1355 m	783.8 m	20 - 30%	25%		Middle Miocene			
										Rancak Fm	Limestone				20 - 30%	25%		Middle Miocene			
										Kujung Fm	Limestone				18 - 30%	24%		Late Oligocene-Early Miocene	Kujung Fm	Shale	Early Miocene
										Ngimbang Fm	Limestone							Eocene	Ngimbang Fm	Shale	Eocene

Table 4.6 (continued)

No	No. (Basin ID)	Basin Name	Basin Status	HC Indication	Tectonic Setting	Basement Type	Geometric Factor	Area (size) (km2)	Average Geothermal Gradient (°C/100m)	Storage System Elements											
										Reservoir Rock (play)									Seal Rocks		
										Formation name	Lithology	Top Formation Depth (Avg) (m)	Thickness (m)		Porosity		Permeability	Age	Formation name	Lithology	Age
													range	average	range	average					
12	37	Kendeng	Producing basin	1273 oil wells, 103 gas wells	Intermontane Basin	granitic, meta sediment, continent of sundaland	72.5	30,278	3.89	Pucangan Fm	Sandstone										
										Rancak Fm	Limestone	965 m		124 m		23%		Middle Miocene	Mundu Fm	Claystone	Pliocene
										Kujung Fm	Limestone	1216 m		762 m		23%		Oligo-Miocene	Kalibeng Fm	Marl	Mio-Pliocene
13	53	Tarakan	Producing basin	1439 oil wells	Passive Margin Deltaic Basin	granitic, meta sediment, continent of sundaland	68.0	81,468	3.57	Tabalar Fm	Limestone							Late Oligocene-Early Miocene	Birang Fm	Shale	Oligo-Miocene
				120 gas wells						Latih Fm	Sandstone							Middle Miocene	Menumbar Fm	Shale	Middle-Late Miocene
				38 oil and gas wells						Tabul Fm	Sandstone		1300-2000	1650			56 - 613 mD	Middle - Late Miocene			
				15 oil and gas shows						Santul Fm	Sandstone							Late Miocene			
				4 unreported wells						Tarakan Fm	Sandstone	608.5	1000-2248	1624	20-21%	20.5%	409.1 mD	Pliocene	Sajau Fm	Shale	Pliocene
										Bunyu Fm	Sandstone	220.0	2885	2885 m	26 %	26%	56 - 576 mD	Pleistocene	Waru Fm	Shale	Pleistocene
14	54	Kutai	Producing basin	2327 oil wells	Passive Margin Deltaic Basin	granitic, meta sediment, continent of sundaland	68.0	130,970	3.03	Sepinggan	Limestone							Pliocene	Intraformational	Shale	
				3135 gas wells						Kampung Baru Fm	Sandstone	123.0	299 - 3800 m	2050 m	18 - 30 %	24%	1 - 3000 mD	Late Miocene			
				1348 oil and gas wells						Balikpapan	Sandstone	456.0	48.3 - 3800 m	1475 m	18 - 30 %	24%	1 - 5000 mD	Middle-Late Miocene			
				24 wells with oil shows						Pamaluan Fm	Sandstone							Early-Middle Miocene			
										Tanjung Fm	Sandstone							Oligocene			
15	55	Barito	Producing basin	169 oil wells, 5 gas wells, 7 wells with oil shows	Rifting Valley Foreland	granitic, meta sediment, continent of sundaland	68.0	59,033	3.56	Lower Tanjung Fm	Sandstone	695.0	256 - 436 m	346 m	22 %	22%	100 mD	Early-Middle Eocene	Upper Tanjung Fm	Mudstone	Late Eocene
16	65	Banggai	Producing basin	10 oil wells, 16 gas wells, 4 wells with oil and gas, 2 wells each with oil show and gas show	Rifting Valley Passive Margin	ophiolitic and metamorphic basement	68.0	43,391	2.84	Minahaki Fm	Limestone	1,871.0		499 m	16 - 26%	23%	1350 mD	Middle-Upper Miocene	Kintom Fm	Shale	Pliocene
										Tomori Fm	Limestone	2,319.0		384 m	10 - 20%	15%		Lower Miocene	Matindok Fm	Shale	Mid Miocene
17	66	Makassar Str	Producing basin	1 oil well, 9 gas wells, 1 well with gas show	Rifting Valley	metamorphic basement	68.0	60,118	2.23	Berai/Tonasa Fm	Limestone	840.0		625 m	12 - 26%	19%		Oligocene	Intraformational	Shale	
										Tanjung/Toraja Fm	Sandstone	1,977.0		265 m	7 - 28%	19%		Eocene			
18	67	Sengkang	Producing basin	18 gas wells, and 1 well with gas show	Rifting Valley	metamorphic basement	69.0	16,945	2.55	Walanae Fm	Sandstone							Late Miocene-Pliocene			
										Tacipi Fm	Limestone	700.0	0-700 m	350 m	25 - 34%	26%	13 - 313 mD	Late Miocene	Walanae Fm	Claystone	Pliocene
19	104	Seram	Producing basin	194 oil wells, 6 wells with oil and gas, 3 gas wells	Passive Margin Trench	oceanic-metamorphic basement	70.0	59,288	3.55	Manusela Fm	Limestone	1,631.0	380.3904	380.3904	6 - 12%	9%		Middle Jurassic	Kola Fm	Shale	Late Jurassic
										Fufa Fm	Sandstone	89.9	199.7 m	199.7 m	28 %	28%	72 mD	Pleistocene	Intraformational	Shale	
20	115	Salawati	Producing basin	683 oil well, 17 well with oil and gas, 25 wells with oil shows	Passive Margin Foreland		68.7	15,329	4.38	Klasaman Fm	Sandstone				20 - 30%	25%		Pliocene	Intraformational	Shale	
										Klasafet Fm	Limestone				18 - 23%	21%		Late Miocene			
										Kais Fm	Limestone	1,287.0	13 - 360 m	110 m	11 - 30 %	19%	6 - 400 mD	Early-Middle Miocene			
										Sirga Fm	Sandstone				12 - 17%	15%		Late Oligocene			
21	117	Bintuni	Producing basin	21 oil wells, 38 gas wells, 3 wells with oil and gas	Passive Margin Foreland		68.0	39,727	3.59	Kais Fm	Limestone	260.0	210 m	210 m	6 %	6%	1 mD	Late Miocene	Steenkool Fm	Shale	Pliocene
										Kembelangan	Sandstone				8 - 18%	13%		Jurassic	Upper Kembelangan	Shale	Cretaceous
										Tipuma Fm	Sandstone				5 - 12%	9%		Triassic			
										Ainim Fm	Sandstone				8 - 12%	10%		Late Permian			

Source: Produced by this study.

An example of data set of West Natuna Basin for CO_2 storage resources estimation in deep saline aquifer is given in Table 4.7. The map and storage elements system for this basin is depicted in Figure 4.4. The basin is tertiary Indonesia rift basin, which lies on Sunda shelf. The basin formation was initially formed by subduction (slab rollback) to the East and divergent strike-slip extrusion faults associated with the India–Asia plate collision and it caused the rifting event which occurred probably in the late Eocene to Oligocene. Gabus formation with reservoir rocks of Late Oligocene Gabus sandstone is identified as a good candidate for saline aquifer.

Table 4.7. An Example Data Set and CO_2 Storage Resources Estimation in Deep Saline Aquifer for West Natuna Basin

Parameter	Unit	Value
Basin Area	km^2	105,456
Formation Name	-	Lower Gabus
Lithology	-	Sandstone
E	**%**	**2**
Top Formation Depth	m	1,653.4
Formation Thickness	m	90
Geometric Factor	fraction	0.68
Average Porosity	%	20
Storage Pore Volume	**m^3**	**1.2908E+12**
Geothermal Gradient	°C/100m	3.92
Surface Temperature	°C	26.67
Formation Temperature	**°C**	**91.5**
Brine Density	kg/m^3	1,200
Standard accelartion due to gravity	m/sec^2	9.8
Formation Pressure	**Pa ($kg/m.sec^2$)**	**19,443,984**
	Mpa	19.44
CO_2 density	**kg/m^3**	**509.44**
CO_2 Storage Resources	**kg**	**1.3152E+13**
	Gt	**13.15**

Source: Produced by this study.

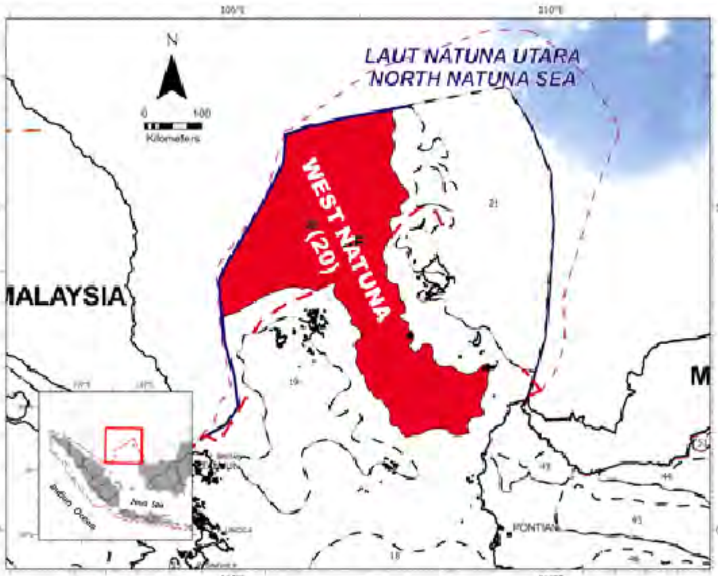
The steps for estimating CO_2 storage resources are as follows:

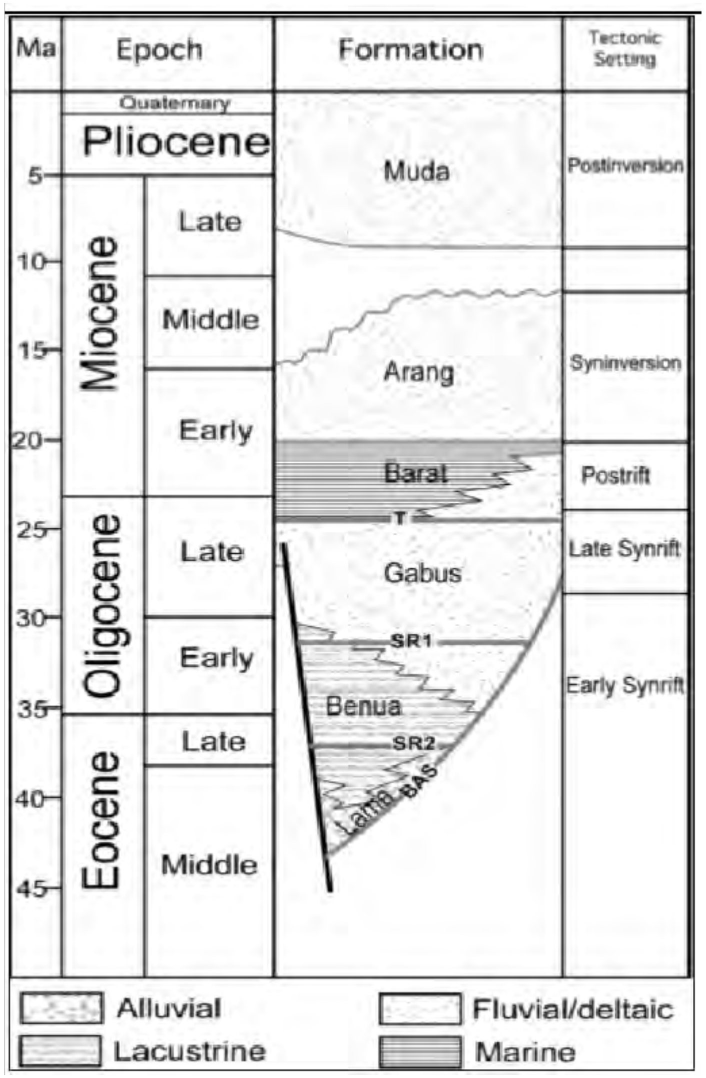
1. Determine storage efficiency, *E*, for given lithology. According to Table 3.5, E_{P50} for sandstone is 2%.
2. Calculate formation temperature, *T*:

$$T = Surface\ Temperature + Geothermal\ Gradient\ \times Formation\ Depth$$

$$T = 26.67 + \frac{3.92}{100} \times 1{,}653.4 = 91.483^{o}C$$

Figure 4.4. Map of West Natuna Basin and its Storage Elements System

Basin ID	20
Basin Name	West Natuna
Basin Status	Producing Basin
Area (km2)	105,456
Geographic Location	Natuna Sea, Western Indonesia
Coordinates	104° 49.525' E - 109° 2.297' E and 1° 26.626' N - 6° 30.584' N
Location Map	 (ESDM, 2022)



Source: Produced by this study. Location map of West Natuna Basin is provided by Geological Agency, Ministry of Energy and Mineral Resources

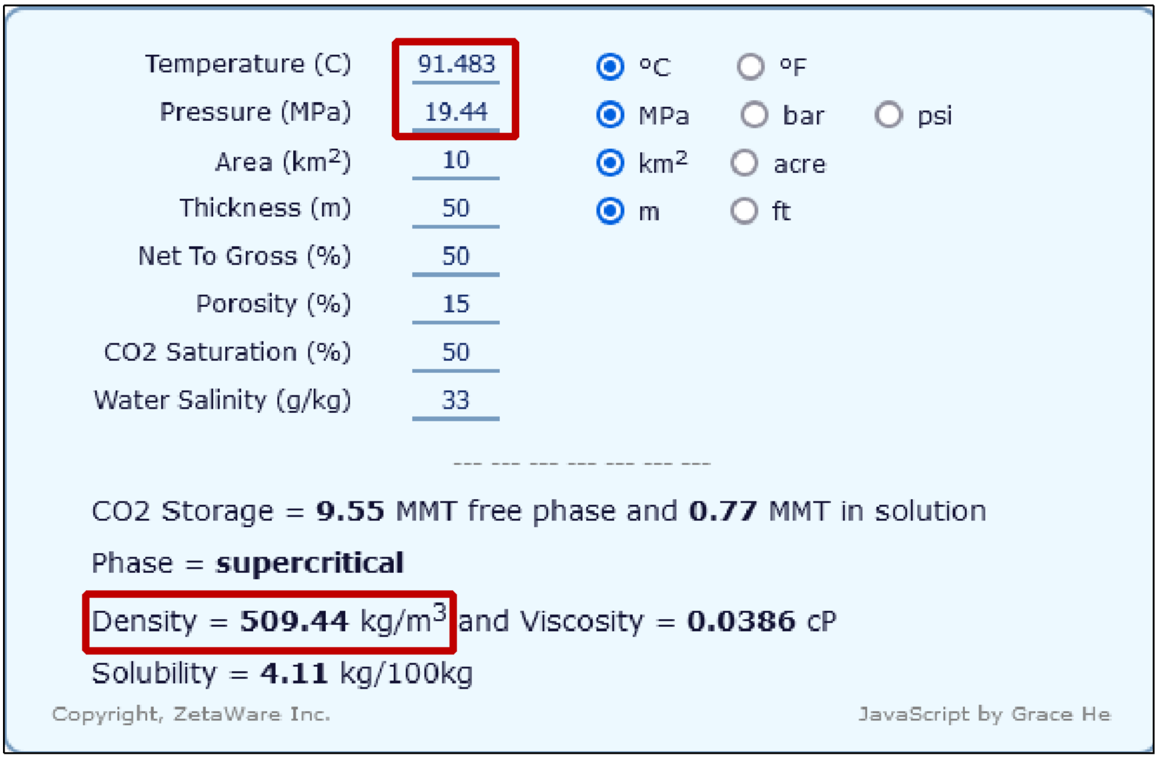
3. Calculate formation pressure, *p*, assuming hydrostatic pressure:

$$p = Brine\ Density \times Acceleration\ due\ to\ Gravity \times Formation\ Depth$$

$$p = 1{,}200 \times 9.8 \times 1{,}653.4 = 19.44\ Mpa$$

4. Calculate CO_2 density by Zetawata tool, which can be accessed via the link https://www.zetaware.com/utilities/CO2. Given *p*, *T*, the CO_2 density is 509.44 kg/m^3, as displayed in Figure 4.5.

Figure 4.5. CO_2 Density Calculation Screen in Zetawata Tool



Note: The Author added the Temperature and Pressure data and the red box square.
Source: https://www.zetaware.com/utilities/CO2 (accessed 22 November 2024).

5. Estimate CO_2 storage resources using Eq. 3.3:

$$M_{CO_2} = A \times h_g \times G_f \times \phi_{tot} \times \rho_{CO_2} \times E \times C_{fs}$$

$$M_{CO_2} = 105{,}456 \times 90 \times 0.68 \times \frac{20}{100} \times 509.44 \times \frac{2}{100} \times 10^{-6}$$

$$M_{CO_2} = 13.15\ Gt$$

3. CO_2 Storage Resources in Oil and Gas Fields

Total CO_2 storage resources in Indonesia's 1,068 oil and gas fields are about 10.14 Gt. The CO_2 storage resources are estimated at 1.31 Gt in 728 oil fields and 8.84 Gt in 340 gas fields. They have been discovered and characterised, but the CO_2 storage project(s) are not yet considered for commercial development. Therefore, they are classified as contingent storage resources as assessed and categorised as the proved denoted as C1. The total probable and possible categories denote C2 and C3 in all oil and gas fields are 1.22 and 1.20 Gt, respectively. Table 4.8 presents the contingent storage resources in oil and gas fields sorted by the total of C1 from largest to smallest. In general, gas fields have more significant CO_2 storage resources than oil fields because of their large size and their higher recovery factor.

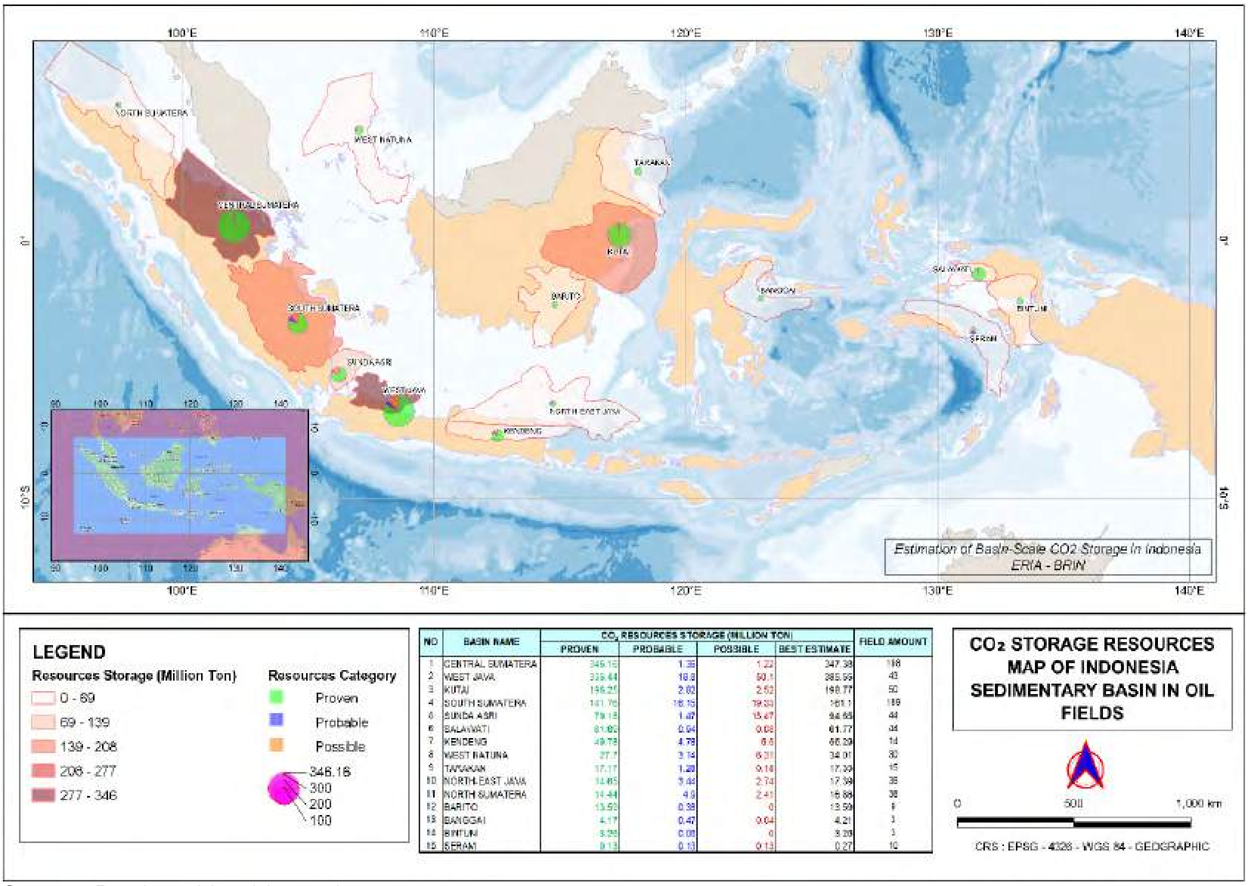
Table 4.8. Summary of Contingent CO_2 Storage Resources in Oil and Gas Fields by Basin Categorised as C1, C2, and C3

NO	BASIN		OIL FIELDS				GAS FIELDS				TOTAL			
			Mt CO_2			NO. OF FIELDS	Mt CO_2			NO. OF FIELDS	Mt CO_2			NO. OF FIELDS
	ID	NAME	C1	C2	C3		C1	C2	C3		C1	C2	C3	
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	54	Kutai	196.25	2.82	2.51	50	3,059.69	349.07	234.86	39	3,255.94	351.89	237.37	89
2	1	North Sumatra	14.44	4.90	2.41	38	1,313.94	54.17	62.01	36	1,328.38	59.07	64.42	74
3	117	Bintuni	3.26	0.06	0.00	3	1,206.11	154.19	277.26	9	1,209.37	154.25	277.27	12
4	15	South Sumatra	141.76	16.15	19.33	189	836.27	101.99	221.77	78	978.03	118.14	241.10	267
5	86	Timor Sea					954.92	255.14	61.34	1	954.92	255.14	61.34	1
6	25	West Java	335.44	18.80	50.10	43	260.45	18.91	18.92	33	595.90	37.71	69.03	76
7	53	Tarakan	17.17	1.28	0.18	15	449.74	19.05	18.47	12	466.91	20.33	18.65	27
8	11	Central Sumatra	346.16	1.36	1.22	198	7.22	3.33	3.35	27	353.38	4.69	4.57	225
9	20	West Natuna	27.70	3.14	6.31	30	225.28	25.56	46.54	21	252.98	28.70	52.85	51
10	37	Kendeng	49.78	4.78	6.54	14	194.97	31.14	17.33	15	244.75	35.92	23.87	29
11	65	Banggai	4.17	0.47	0.04	3	173.69	107.24	78.39	6	177.86	107.24	78.39	9
12	23	Sunda Asri	79.18	1.47	15.47	44	26.65	6.90	10.30	32	105.83	8.36	25.77	76
13	115	Salawati	61.69	0.94	0.08	44	10.61	0.00	0.00	12	72.29	0.94	0.08	56
14	36	Northeast Java	14.65	3.44	2.74	38	51.94	28.00	34.13	10	66.59	31.44	36.87	48
15	67	Sengkang					43.45	0.00	0.00	5	43.45	0.00	0.00	5
16	55	Barito	13.59	0.38	0.00	9	2.38	0.00	0.00	2	15.98	0.38	0.00	11
17	66	Makassar Strait					12.76	3.55	4.94	1	12.76	3.55	4.94	1
18	35	Bawean					5.98	4.02	3.67	1	5.98	4.02	3.67	1
19	104	Seram	0.13	0.13	0.13	10					0.13	0.13	0.13	10
TOTAL			**1,305.37**	**60.13**	**107.08**	**728**	**8,836.05**	**1,162.25**	**1,093.29**	**340**	**10,141.42**	**1,221.91**	**1,200.32**	**1,068**

Source: Produced by this study.

Figure 4.6 presents a map of CO_2 storage resources distribution in oil fields by basin, presented as C1, C2, and C3 categories. The CO_2 storage resources in oil fields distributed are mainly in Central Sumatra, West Java, Kutai, and South Sumatra basins (Figure 4.7). Cycle radius reflects the size of CO_2 storage resources. Most of these top five basins located in Western Indonesia and account for 84% of total CO_2 storage resources in the country's oil fields. Plotting the CO_2 storage resources with the number of fields on the same graph makes it easy to understand how scattered the resources. The top of the Central Sumatra Basin has 346 Mt scattered in 198 oil fields. West Java basin ranked second, with 335 Mt spread across 43 oil fields. Comparing these two basins shows that CO_2 storage resources in the West Java basin are more concentrated than in Central Sumatra, which are widely spread. This finding is useful in deploying a CCS/CCUS regional hub.

Figure 4.6. Map of CO_2 Storage Resources Dispersion in Oil Fields by Basin Presented as C1, C2, and C3 Categories

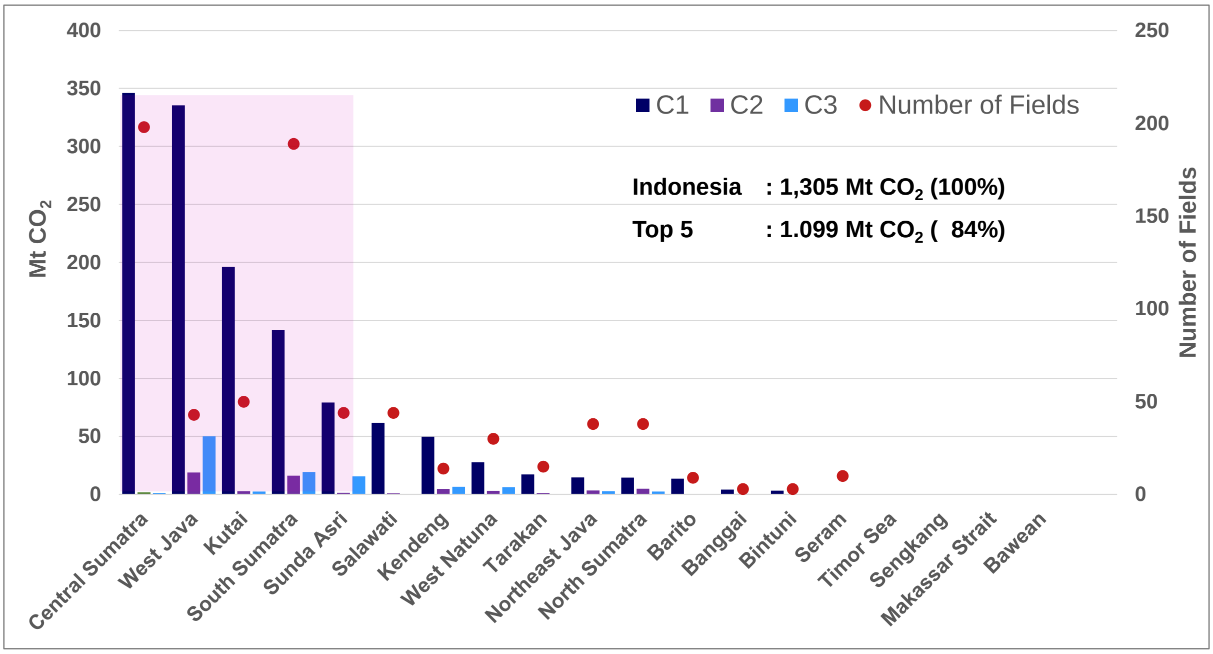


NO	BASIN NAME	CO_2 RESOURCES STORAGE (MILLION TON)				FIELD AMOUNT
		PROVEN	PROBABLE	POSSIBLE	BEST ESTIMATE	
1	CENTRAL SUMATERA	346.16	1.36	1.22	347.38	198
2	WEST JAVA	335.44	18.8	50.1	385.56	43
3	KUTAI	196.25	2.02	2.52	198.77	50
4	SOUTH SUMATERA	141.76	18.15	19.33	161.1	189
5	SUNDA ASRI	79.15	1.47	15.47	94.65	44
6	SALAWATI	61.82	0.94	0.08	61.77	44
7	KENDENG	49.78	4.78	6.6	66.29	14
8	WEST NATUNA	27.7	3.14	6.31	34.01	30
9	TARAKAN	17.17	1.28	0.14	17.39	15
10	NORTH EAST JAVA	14.65	3.44	2.74	17.39	35
11	NORTH SUMATERA	14.44	4.9	2.41	16.88	38
12	BARITO	13.52	0.38	0	13.59	9
13	BANGGAI	4.17	0.47	0.04	4.21	1
14	BINTUNI	3.28	0.08	0	3.28	1
15	SERAM	0.13	0.13	0.13	0.27	10

Source: Produced by this study.

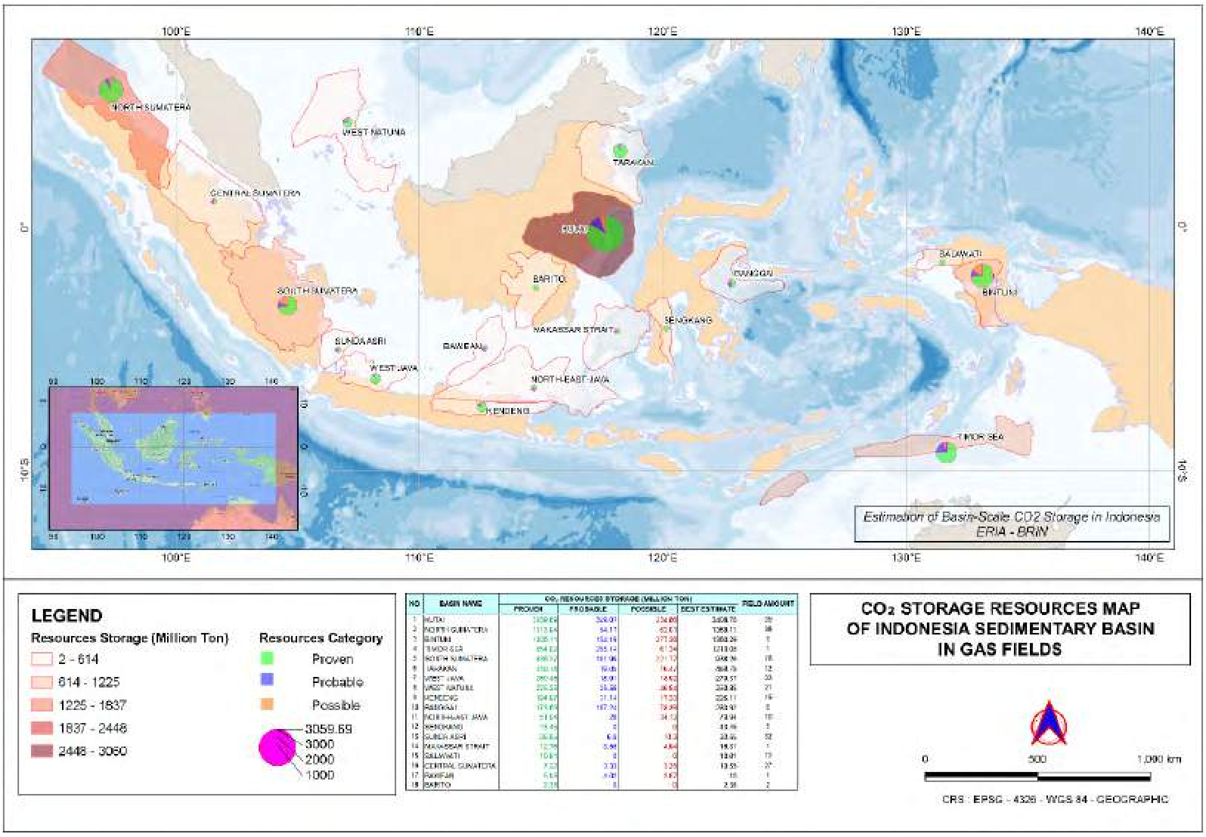
Figure 4.8 depicts a CO_2 storage resources dispersion map in gas fields by basin, presented as C1, C2, and C3 categories. The dispersion of CO_2 storage resources in gas fields is mainly in Kutai, North Sumatra, Bintuni, Timor Sea, and South Sumatra basins (Figure 4.9). These top five basins account for 83% of total CO_2 storage resources in Indonesian gas fields mostly situated in the eastern part, in contrast with the dispersion of CO_2 storage in oil fields. This difference in terms of location is that the oil mostly produced in the western part and the gas produced come substantially from basins in the eastern part of Indonesia.

Figure 4.7. Histogram of CO_2 Storage Resources in Oil Fields by Basin



Source: Produced by this study.

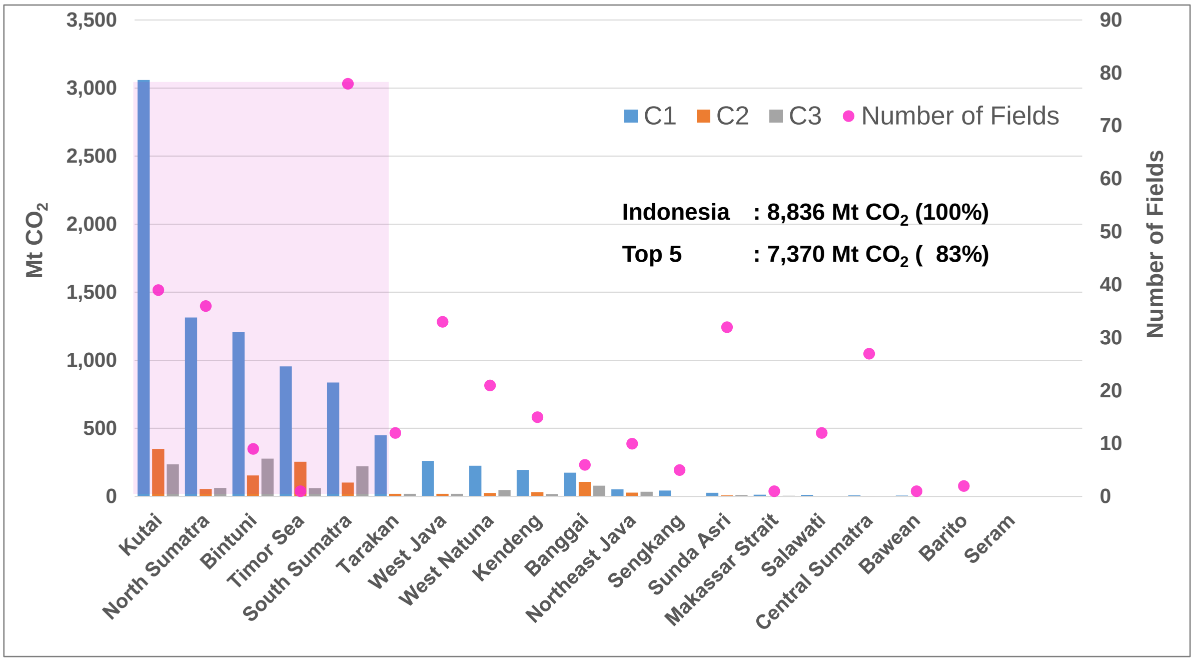
Figure 4.8. Map of CO_2 Storage Resources Dispersion in Gas Fields by Basin Presented as C1, C2, and C3 Categories



Source: Produced by this study.

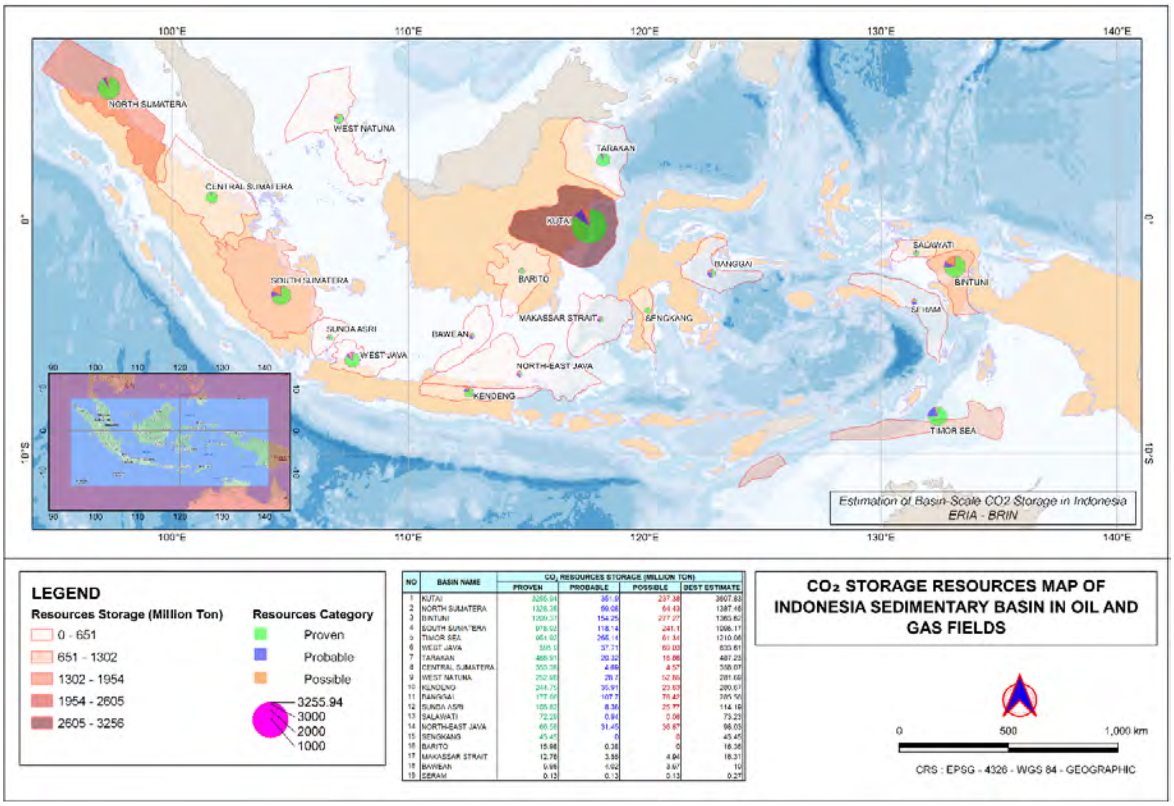
Figures 4.10 and 4. 11 show the map of total CO_2 storage resources dispersion in oil and gas fields by basin presented as C1, C2, and C3 categories. The distribution of CO_2 storage resources both in oil–gas fields and in gas fields are the same. The attribution to the size of gas fields pore volume is substantially higher than the oil fields.

Figure 4.9. Histogram of CO_2 Storage Resources in Gas Fields by Basin



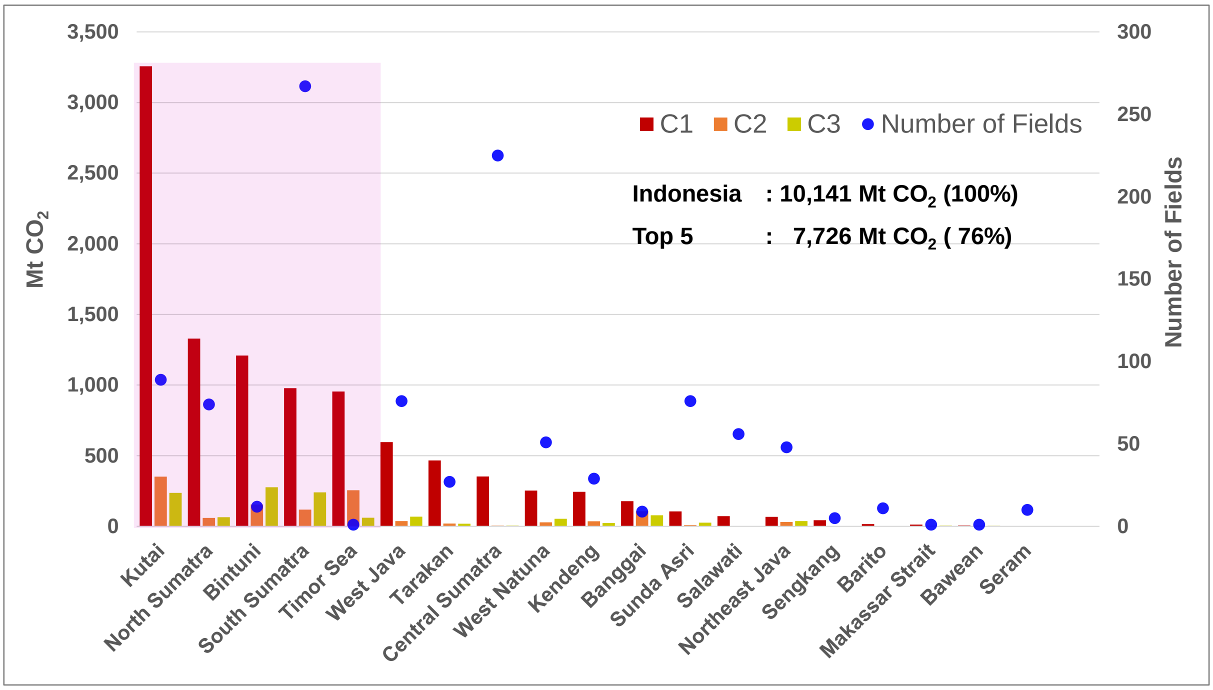
Source: Produced by this study.

Figure 4.10. Map of CO_2 Storage Resources Dispersion in Oil and Gas Fields by Basin Presented as C1, C2, and C3 Categories



Source: Authors.

Figure 4.11. Histogram of CO_2 Storage Resources in Oil and Gas Fields by Basin



Source: Produced by this study.

Figure 4.11, which presents the CO_2 storage distribution in oil and gas fields, can provide insights into CCUS hub development and support policymakers with respect to scale deployment of individual or cluster storage sites.

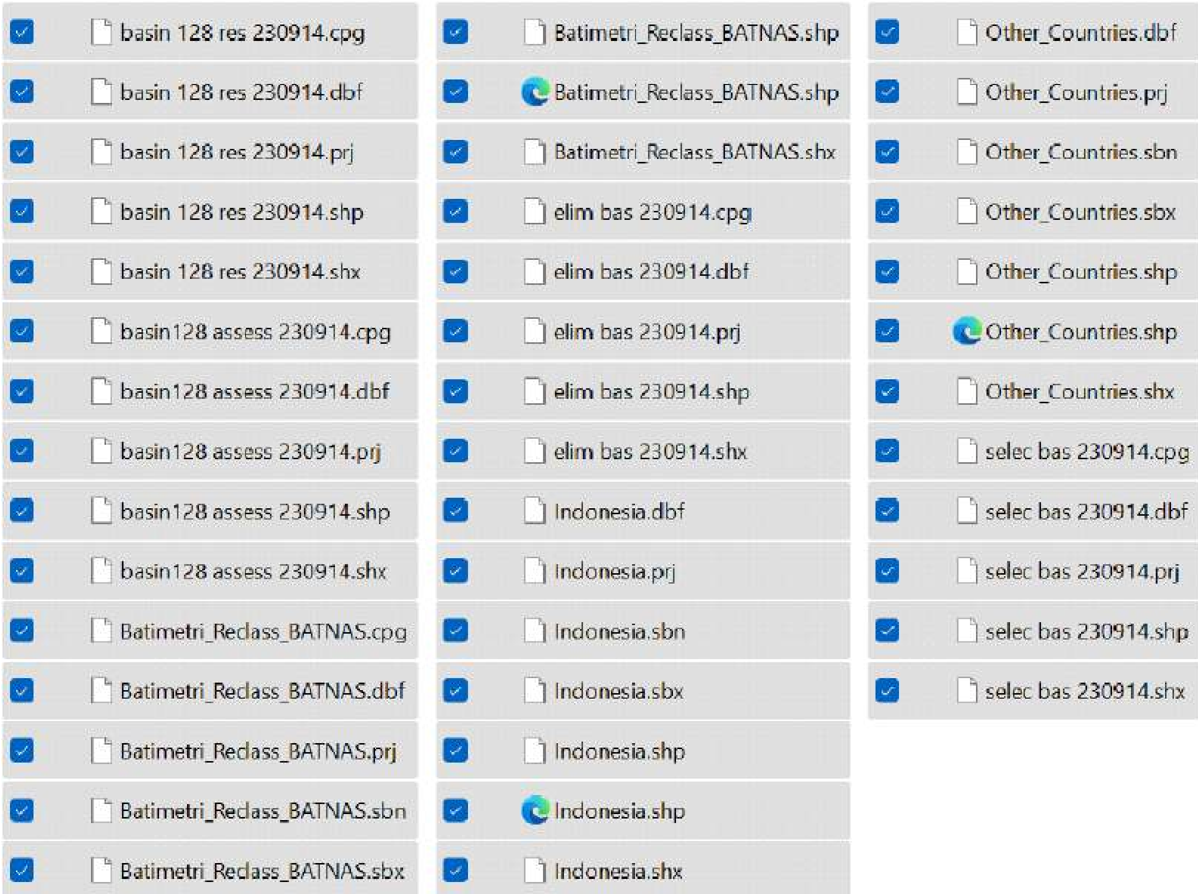
4. GIS for Indonesia's CO_2 Storage Resources

In this study, the capability of a GIS framework is harnessed to establish and visualise the dispersion of CO_2 storage resources over Indonesia's sedimentary basins. The development of a GIS framework includes inputting the estimation results as attributes on the basin map and then creating a map layout.

GIS analysis is a significant component of CCUS studies that aids in the collection, maintenance, storage, analysis, output, and display of geographically referenced spatial data and information. The GIS can provide visual representation of the data both on-screen and through the production of large- and small-scale images and printed maps. It also offers a highly flexible, easily database and display tool that facilitates the spatial analyses required to solve complex linking of CO_2 sources with appropriate and cost-effective sinks (Yousefi-Sahzabi et al., 2011).

A GIS-based tool for viewing CCUS potential across Indonesia's sedimentary basins has been developed for this study. The data set for this tool is given in Figure 4.12. The tool displays dispersal of the CO_2 storage resources by basin that have been estimated at the basin-scale in saline aquifers and the field-scale in hydrocarbon reservoirs within the selected basins.

Figure 4.12. Established Data Set for Basin-scale CO_2 Storage Assessment in Indonesia



Source: Produced by this study.

Chapter 5
Conclusions

Of the many aspects discussed in the preceding chapters, the main conclusion can be summarised as follows:

- IEA Net Zero by 2050 Roadmap for the global energy sector underscores the critical role of CCUS technologies in putting the world on a path to net-zero emissions, contributing more than 10% of cumulative emissions reductions globally to 2050.
- Regional cooperation and shared infrastructure can support faster deployment of CCUS in Southeast Asia. A hub approach will support economies of scale and kick-start deployment CCUS in the region.
- There are worldwide plans for more CO_2 capture volumes over the next 5 years from the current level of around 40 Mt CO_2 per year to 1.6 Gt CO_2 in 2030, and a rapid expansion to 7.6 Gt CO_2 over the following 25 years. In Southeast Asia, CCUS would build from a limited base today to 200 Mt or more in 2050.
- Around 95% of total CO_2 captured in 2050 is stored in permanent geological storage. Identifying and determining CO_2 storage resources are key issues in taking CCUS forward.
- Indonesia offers excellent opportunities for CCUS deployment in the region because of the availability of vast sedimentary basins that contain geological media suitable for CO_2 storage, such as oil and gas reservoirs and deep saline aquifers.
- A total of 128 sedimentary basins exist across the Indonesian archipelago. Twenty of them contain oil and gas reservoirs that have been proven to store significant quantities of buoyant fluids, such as oil, gas, and CO_2. The rest are 27 discovery basins but not yet production, 12 prospective basins with seismic and well data available, and 69 unexplored basins.
- Oil and gas reservoirs are prime candidates for CO_2 storage because they have been proven to store significant quantities of buoyant fluids, such as oil, gas, and CO_2. They have been extensively studied and have large amounts of geological and engineering data available for detailed site characterisation.
- Many studies have identified saline aquifers to be one of the best potential options for large volume geological storage of CO_2 and extensive spatial distribution in most sedimentary basins, although commonly less understood and typically include significant uncertainty due to the lack of subsurface data.
- Several studies of CO_2 storage resources have been conducted in selected sedimentary basins of Indonesia. The storage resources were estimated up to 69 Gt in the selected saline aquifers in the Northwest Java, East Java, North Sumatra, Central Sumatra, and South Sumatra basins. The CO_2 storage resources in assessed

oil and gas reservoirs were estimated at 2.5 Gt for an optimistic level in 12 hydrocarbon fields. The results appear small, suggesting that all available pore volume across sedimentary basins of Indonesia may not have been evaluated.

- This study is more advanced than others because it ranks the 128 sedimentary basins in terms of CO_2 storage suitability, CO_2 storage assessment with level of estimation ranging from basin-scale for saline aquifers to field-scale for hydrocarbon reservoirs in selected sedimentary basins, classifies the quantitative estimates of CO_2 storage in terms of data availability, and integrates the results into a GIS-based tool.
- Elimination and selection screening processes have been synthesized to evaluate the overall suitability of Indonesia's sedimentary basins for CO_2 storage. The elimination process using the minimum depth of 800 m ruled out 32 sedimentary basins. These 32 basins are then excluded from the selection process for quantifying CO_2 storage suitability and ranking.
- Sixteen screening criteria for the selection process are defined and grouped into four categories related to data availability, storage potential, security, and environment to determine its relative importance among the set of criteria. A pairwise comparison approach is applied to the weight of each criterion.
- A sedimentary basin database for Indonesia has been established to perform a screening and ranking basin for assessing their suitability of CO_2 storage. This database used to estimate the CO_2 storage resources in deep saline aquifers and hydrocarbon fields. Data are collected from multiple database sources.
- Sedimentary basins listed on the top ranking in terms of their suitability for CO_2 storage dominated by producing basins due to high weighting factor. They are attributed to large basin size, location in onshore to shallow water depth, situated in an area with relatively stable geological activity, and have low geothermal gradient than others.
- A new approach in estimating CO_2 storage resource in deep saline aquifers has been introduced by adding a trap geometric multiplier into the volumetric equation to appropriately represent the effective average of closure area.
- Indonesia's CO_2 storage resources in deep saline aquifers are estimated at 680.57 Gt distributed in 21 sedimentary basins and classified as prospective storage resources (3U). Kutai Basin shows significant CO_2 storage resources of 152.95 Gt.
- CO_2 storage resource in oil and gas fields is defined on a volumetric basis and estimated based on reserves databases that reported the OOIP, OGIP, and RF_{EUR} for each field, which is under development or approved for development. Assessed are 1,068 fields, comprising 728 oil fields and 340 gas fields.
- Indonesia CO_2 storage resources in hydrocarbon fields are estimated at 1.30 Gt in 728 oil fields and 8.84 Gt in 340 gas fields. They are classified as contingent storage resources as of the cutoff date when this assessment was conducted, and categorised

as C1. The total probable and possible categories denoted as C2 and C3 in all oil and gas reservoirs are 1.05 and 1.03 Gt, respectively.

- Indonesia's significant potential of CO_2 storage in both deep saline aquifers and hydrocarbon fields makes it well suited to be part of the regional CCUS hub.
- A GIS-based tool for viewing CO_2 storage resources across the country's sedimentary basins has been developed. The tool allows to display distribution of the CO_2 storage resources by basins and distinguish the category of contingent CO_2 storage resources in hydrocarbon fields.

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