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Reduction of Carbon Emission in East Java Power Generation Sector Through The Use of Saline Aquifer as CO_2 Storage - A Conceptual Study

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ABSTRACT - East Java region, as one of the most industrialized regions in Indonesia, is a significant contributor to national greenhouse gas (GHG) emissions, and therefore may play a significant role in supporting the national commitment to reach net zero emissions (NZE). This study is made to provide an example of how a conceptual CCS scheme using a saline aquifer is applied in the region. Tanjung Awar-awar coal-fired power plant, which is located in the Tuban city area on the northern coast of East Java, is selected as the GHG source. With its power generation capacity of 2 x 350 MW, it emits 4.5 Mt CO_2e annually. The extensively distributed Kujung carbonate formation is chosen as the CO_2 saline aquifer storage. Amidst the typical data rarity commonly faced in preliminary studies on saline aquifers, modeling for CO_2 storage has been performed using all available primary and secondary data from all available sources. The most likely estimate of storage resource shows 479 Mt CO_2e (status: 3U in SRMS classification system), with its A2 block possessing 162.78 MtCO_2 storage resource. The CO_2 injection scheme is essentially a volumetric balancing between CO_2 emissions and injection rates through injection wells. Well injection capacities are estimated, and must be able to cope with CO_2 emissions from the power plant. Accordingly, two CCS scenarios of 50% CO_2 capture (Scenario A; 4,671 tons/day) and 100% CO_2 capture (Scenario B; 9,342 tons/day) are set. To serve the two scenarios, four (4) and eight (8) horizontal wells are needed, respectively. A similar approach has also been made for vertical injection wells. Following the assumptions set in the CCS scheme, a total of 34,098,300 tons and 68,189,300 tons of CO_2 can be stored in a 20-year injection permit for Scenario A and Scenario B, respectively. Nonetheless, these Figures constitute just fairly small fractions of the Kujung A2 block's storage resource. This shows the huge potential of the Kujung Formation to act as a saline aquifer storage for CCS schemes in the East Java region. This also presents the potential of the Kujung Formation to sustain multi-CO_2 sources and prolonged injection schemes. Despite many challenges faced, especially in relation to data scarcity, the results may serve as a reference for more detailed project-based studies in the future.

Keywords: CO_2 emissions, carbon capture and storage (CCS), East Java, Tanjung Awar-awar power plant, saline aquifer, Kujung Formation, CO_2 injection wells

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INTRODUCTION

In the year 2021 Indonesia updated its nationally determined contribution (NDC) to reduce greenhouse gas (GHG) emissions in 2030 by 31.9% (≈915 million tons CO_2 equivalent, Mt CO_2e) with its own effort and by 43.1% (≈1.185 Mt CO_2e) with international support (Presidential Regulation, Peraturan Presiden No.98/2021). This is a part of Indonesia's national commitment to achieve net zero emissions (NZE) in year 2060 or earlier. These reduced Figures are expected to be fulfilled by reductions primarily in the sectors of agriculture and forestry (89%), while the rest is contributed by energy, waste, industry, and transportation sectors (Figure 1). The reductions in GHG emissions are to be achieved through energy conservation and the use of new energy sources. During the transitional period, means for keeping the GHG as low as possible need to be implemented. One of these measures is carbon capture and storage (CCS) and carbon capture, utilization, and storage (CCUS).

In relation to the CCS/CCUS implementation, the Ministry of Energy and Mineral Resources of the Republic of Indonesia has launched a ministerial regulation (Peraturan Menteri ESDM No. 2 2023) regarding CCS/CCUS operations in oil and gas working areas, with GHG sources encompassing all possible sources. One of the most important aspects of the activities is the need for GHG (e.g CO_2) storage in subsurface geological formations such as depleted oil/gas reservoirs, deep saline aquifers, and unmineable coal seams (e.g Reza et al., 2019; Rashid et al., 2020). In these oil/gas reservoirs and deep coal seams, injected CO_2 is utilized in the enhanced oil/gas recovery schemes (CCUS), while in water-bearing rocks, also commonly known as the saline aquifer, the gas is stored permanently under various mechanisms. Accordingly, efforts must be spent to study, understand, and prepare the underground CO_2 storage designated to support the CCS/CCUS schemes.

Various studies have been made to understand the nature of CO_2 storage and its storage resources. For instance, the Ministry of Energy and Mineral Resources (MESDM, 2023) in a macro-basin scale evaluation had estimated Indonesia's CO_2 storage resources of 4.85 gigatons (Gt) in depleted oil/gas reservoirs and 572 Gt in saline aquifers within the productive 21 sedimentary basins. In this macro-scale study, like one performed by Iskandar et al. (2013), sedimentary basins in Indonesia are ranked in their favorability for CO_2 storage. Closer looks at field or site scales, nevertheless, are also performed. Some CO_2 source and sink matching studies at lower levels (regional levels) have been carried out, such as ones by Sugihardjo et al. (2012), Usman et al. (2021), Sugihardjo (2021), Panggabean et al. (2022), and Susantoro et al (2023). Studies that report various CCS/CCUS projects in Indonesia have also been made and published. Ramadhan et al. (2024) present a summary of projects in Indonesia along with their current status and potential CO_2 storage resources in the projects. The study also presented reports of storage resources in gas fields in Java and Sumatra (Zhang & Lau 2022), and oil/gas fields in Kalimantan (Borneo) (Bokka & Lau 2023). With regards to the ongoing preparation for CCS/CCUS projects the report also present CCS projects such as Arun CCS hub (Wibowo 2020), East Kalimantan CCS (Lau 2023), and Central Sumatra CCS/CCUS (Abdurrahman et al., 2015), CCUS projects like Tangguh CCUS-EGR (Dewanto et al, 2022), Gundih CCUS-EGR (Mulyasari et al., 2021), Sukawati CO_2-EOR (Marbun et al., 2021), Ramba CO_2-EOR (Abdurrahman et al., 2015), coal to dymethil ether (DME) (Umar et al., 2024), methanol – Balikpapan refinery (ADB 2013), and Jatibarang field CO_2 huff n puff (Bungsu et al., 2018). Most of the projects are projected to commence in various forms within the coming decade. The committed GHG emission reduction for energy and industrial sectors of Indonesia's NDC in 2030 is merely about 5% in total. This Figure reflects the sectors' GHG emissions that are hard to abate in the face of the country's need to sustain its economic growth. As reported by Azmi et al. (2022), the needed growth of national electricity is around 6.9% annually. The vast majority of the power plants to sustain this growth are fossil fuel-fired (coal, natural gas, and diesel fuel) ones. This results in an average national emission factor of 5.14 $kgCO_2$ per kilowatt-hour ($kgCO_2$/kWh) of generated electricity. Using this average emission factor carbon footprint over electricity demand per year is estimated to be 6,482 $kgCO_2$ in 2024 and 10,487 $kgCO_2$ in 2045.

As one of the most populous and industrialized regions in Indonesia, East Java province provides examples. Paiton, Pacitan, and Tanjung Awar-awar main power plants in the province are essentially coal-fired with some limited co-firing schemes. Adjacent power plants like Rembang in Central Java province are also coal-fired in nature (Othman et al., 2008, Openinframap 2024). As countries and companies are becoming more involved in pursuing the NZE condition, CCS/CCUS schemes are increasingly seen as the most promising solution, especially for the hard-to-abate sectors like the power generation sector. It is the purpose of this study to provide a preliminary feasibility over a CCS scheme in East Java's power generation sector. This essentially CO_2 source-sink matching study takes Tanjung Awar-awar coal-fired power station, situated in the coastal city of Tuban area (Figure 1), as the sole CO_2 source and uses the nearby saline aquifer (Kujung Formation) as the sink. It is hoped that this conceptual study will result in CO_2 storage resource/capacity availability and the CO_2 transportation/injection scenario. The study may serve as a preliminary overview of the feasibility of CCS/CCUS application for the Tanjung Awar-awar power plant, in particular, and for the region in general.

METHODOLOGY

The study area is located in the northeast part of Java island, and geographically is located between longitude (111.5 - 113.75) degrees east and latitude (6.5 - 7.75) degrees south. Figure 1 depicts the northeast part of East Java province, which geologically is located in the Northeast Java Basin. There are several power generation plants in the region, and the Tanjung Awar-awar power plant (PP) has been selected as the case study due to its medium size and relatively young age.

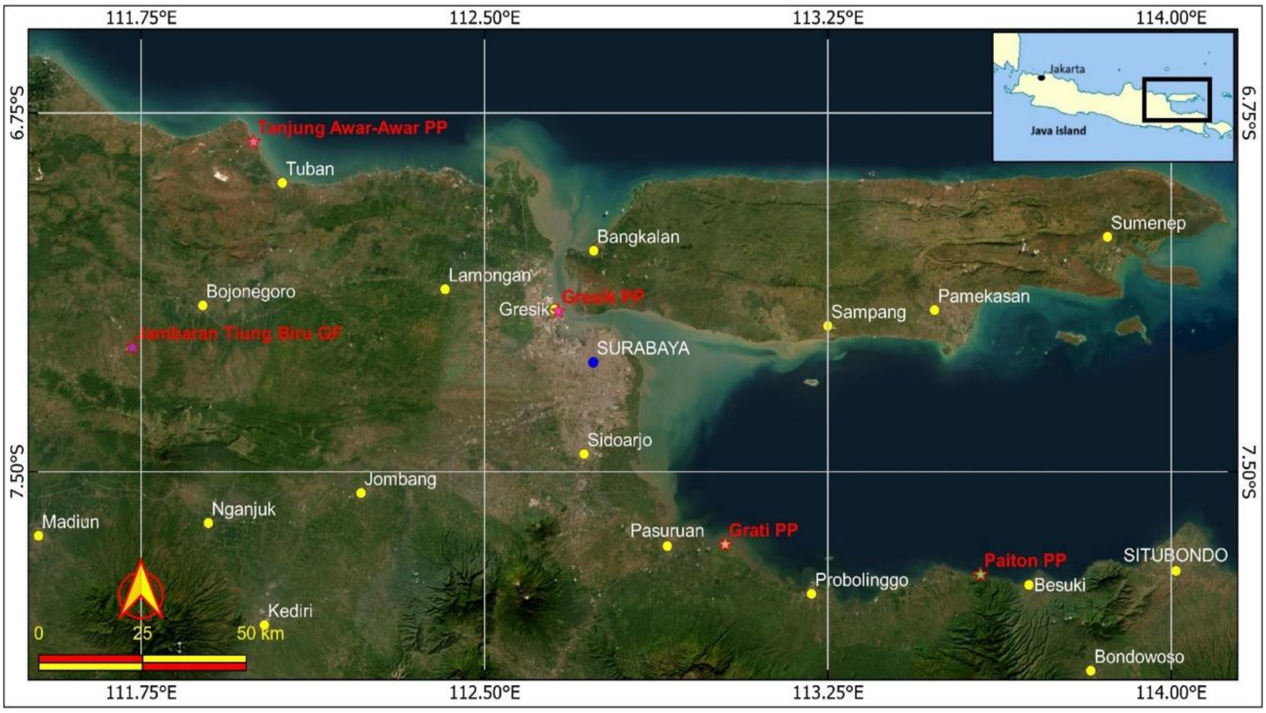

Figure 1. Cities, power generation plants (PP), and gas plants (GP) in the northern part of East Java province. The Tanjung Awar-awar coal-fired power plant is located in the area northwest of Tuban city in the northern coast of East Java. The inset image shows the studied area.

The study of CO_2 storage for the Tanjung Awar-awar coal-fired power plant (PP) begins with a review of literature data and previous studies related to the CO_2 storage in the region. The map of the North East Java sedimentary basin is used as the primary reference for this study. The map has been obtained from Indonesia's Sedimentary Basin map issued by the Ministry of Energy and Mineral Resources in 2022 (MEMR 2022). This map has been combined with CO_2 source data issued by the Directorate General of Electricity - MEMR in 2023 (MEMR 2023a). Important information has also been drawn from data on the potential CO_2 geological storage in Kujung Formation - as well as other formations – from a study by LEMIGAS in 2004 (LEMIGAS 2004). Field survey data issued by the Geological Agency of the Ministry of Energy and Mineral Resources in 2023 (MEMR 2023b) and other secondary data obtained from scientific publications have also been added to the study. Additionally, a geographic information system (GIS) using Quantum GIS software version 3.22.5 (Biatoweiza) is applied, in which data can be separated according to its type into points, lines, and areas (polygons). Each data point is stored as a separate data layer. This data includes sedimentary basins, subsurface maps of the saline aquifer CO_2 storage within the Kujung Formation, and the coal-fired power plants. Each data layer is tied to a single projection reference system, the WGS 84 - Geographic Coordinate System (latitude and longitude).

To obtain the volumetric bulk of the Kujung Formation that has been selected for CO_2 storage, digitization is carried out on the top structure map of the Kujung Formation, still in milisecond, and is converted to depth (in meters). Net thickness of the Kujung Formation within the interval of 800 - 2500 meters, the interval deemed suitable for CO_2 injection in supercritical form (e.g Zhou et al., 2008), is estimated by considering the information on the isochore map of the Kujung formation. The thickness map of the Kujung formation within the 800 - 2500 meter interval is processed into digital elevation model (DEM) data using the Global Mapper application. By obtaining DEM as a potential storage, GIS-based bulk volume calculations can be carried out. The workflow follows: 1) rectification of map coordinates to the WGS 84 Geographic Coordinate System, 2) digitization of top structure contours and isochores, 3) migration of milli-second values to meters, 4) mapping of the thickness contour of the Kujung formation within 800 - 2500 meters interval, 5) transformation of the WGS 84 geographic coordinate system to the WGS 84 UTM system, 6) transformation of contours to DEM, and 7) calculation of the volume of the Kujung rock formation (in cubic meters).

Estimation of the petrophysical value of the Kujung saline aquifer is done by analogy to key well data having similar sedimentary facies. Using the management of all GIS-based data, then through the process of overlaying locations of the key wells and injection areas with the sedimentary facies map, the relationship between the two with the sedimentary facies can be readily identified. Peripheral buffering following several radial distances (50 km, 75 km, and 100 km) is then made to determine which part of the Kujung Formation to be studied. By combining the overlying and the buffering, the area designated for CO_2 saline aquifer storage is studied and then determined.

CO_2 storage resource in saline aquifer

In this study, by considering the level of geological security in Indonesia, which generally has high seismic intensity and presence of volcanic paths, as well as to limit the depth range regarded to be suitable for storage of CO_2 in under supercritical state (e.g IPCC, 2005), interval for the storage is limited within the depth range of 800 – 2500 m ss.

The CO_2 storage resource assessment is basically made through four basic stages: 1) Estimation of bulk volume of the formation to be used as CO_2 storage (aided by the use of Geographic Information System, GIS); 2) Estimation of pore volume of the formation; 3) Estimation of CO_2 density at storage depths; and 4) Estimation of part of the pore volume that can serve as CO_2 storage when it becomes stationary. It has been assumed that the selected area in the Intra Kujung Formation is an open model or at least partially open system, in which all displaced formation brine may move freely into farther parts of the storage away from the injection points (Zhou et al, 2008). In this system, pressure buildup in the storage due to CO_2 injection is not a limiting factor. The widely distributed Kujung formation in the North East Java Basin can be regarded as fulfilling this assumption. In this open system, two methods are commonly applied by many estimations of CO_2 storage resources, the US DOE Capacity Working Group and the CSLF methods (CSLF, 2008; Bachu et al., 2007; US DOE-NETL, 2008; US DOE, 2010).

The DOE method is a volumetric approach that calculates a mass stored CO_2 (GCO_2) based on an investigated area (A), formation thickness (h), porosity (Ø), and CO_2 density (ρ_{CO2}) with the application of a storage coefficient (E), as presented in Equation 1.

$$G_{CO2} = A * h * \emptyset * \rho_{CO_2} * E \quad (1)$$

The E efficiency factor considers a series of variables that may limit the ability of injected CO_2 to occupy 100% of the pore space in a given formation, including geologic heterogeneity, gravity or buoyancy effects, and sweep efficiency. The E values usually fall within the range of 1 % to 4 %. This is under the assumption that CO_2 injection wells can be placed regularly throughout the formation to maximize storage and that the saline formation is an open system. The theoretical estimate of storage resource, as related to the DOE and CSLF methods, is that the total pore space of the assessed formation is reachable by the CO_2 injection. The two methods only differ at this point by the inclusion of irreducible water saturation, in which the CSLF method maintains that the theoretical storage resources are the pore space minus the irreducible water saturation. Within this irreducible water saturation, additional CO_2 storage is expressed in the form of soluble CO_2 in formation water. Nevertheless, since this study aims at estimating the possible CO_2 storage resource during the power plant's lifetime (i.e CO_2 dissolution requires significantly longer time to occur), the DOE method for CO_2 storage resource estimation is adopted in this study.

Gorecki et al (2009) introduced the concept that the storage efficiency coefficient E in Equation 1 is a product of some components consisting a geological volumetric term of E_{geol} that expresses the pore space available for storage, a volumetric displacement term of E_V that expresses the portion of the pore space occupied by CO_2 as a result of macroscopic displacement, and term of E_d that represents the effect of microscopic (pore scale) displacement processes following

$$E = E_{geol} * E_V * E_d \quad (2)$$

where the E_{geol} is defined as

$$E_{geol} = E_{hn/hg} * E_{An/At} * E_{\emptyset e/\emptyset t} \quad (3)$$

with $E_{hn/hg}$, $E_{An/At}$, and $E_{\emptyset e/\emptyset t}$ are related to net-to-gross thickness ratio, fraction of formation area suitable for storage, and fraction of formation total porosity having interconnection, respectively. These Equations 2 and 3 are used in the determination of E in this study.

Using a database of hydrocarbon reservoir properties for >20,000 reservoirs from around the world, Gorecki et al (2009) yielded probabilistic values of P10, P50, and P90 for the storage efficiency coefficient E for various depositional environment using Monte Carlo simulation of CO_2 plume spread for various conditions of depth, pressure, temperature, structure, permeability anisotropy, irreducible water saturation, and injection rate. Goodman et.al (2011; 2016) used log-odds normal distributions for the data used by Gorecki et al (2009) to arrive at more robust estimates of the CO_2 storage efficiency coefficient E at the formation scale. This storage efficiency has been used in the 3rd edition of the National Atlas of CO_2 storage capacity of the United States and Canada (US DOE 2010). In the report, the efficiency values are summarized and presented in the form of probabilistic values of P_{10} and P_{90} (Table 1). The values of efficiencies in Table 1 are referred to whenever primary data for Kujung Formation is not available.

CO_2 injection scheme

The CCS scheme that is adopted for this study is a simple CO_2 volume matching between volumes of CO_2 emissions and CO_2 storage resource in the designated section of Kujung saline aquifer formation. The CCS injection scheme follows the principles and assumption of: 1) Calculations in the CO_2 volume balance involving CO_2 sources and sinks only, and any losses in processing and transmission are not acounted for; 2) CO_2 capture process follows two (2) scenarios of CO_2 capture from 50% flue gas (scenario A) and CO_2 capture from100% flue gas (scenario B); 3) CCS scheme is performed within the basic CO_2 injection permit period of 20 years (MEMR 2023c); 4) number of injection wells involved are determined by estimated injection capacity of individual well; 5) no changes in injectivity capacity and injection rate throughout wells' injection lifetime; 6) the storage is assumed as following an open-system, in which no pressure build-up occurs that may lead to decrease in injectivity, caprocks failure, and faults re-activation; and 7) all injection wells start operation in the first year of the 20 year injection period. The supercritical

Table 1. Efficiency, E (in P10 and P90) values for saline aquifers derived from US DOE (2010).

Term	Symbol	P_{10}/P_{90} values by Lithology			Description
		Clastics	Dolomite	Limestone	
Geologic terms used to define the entire basin or regional pore volume					
Net-to-total area	$E_{An/At}$	0.2/0.8	0.2/0.8	0.2/0.8	Fraction of suitable area for storage
Net-to-gross thickness	$E_{hn/hg}$	0.21/0.76	0.17/0.68	0.13/0.62	Fraction of minimum porosity and permeability suitable for storage
Effective-to-total porosity	$E_{\emptyset e/\emptyset t}$	0.64/0.77	0.53/0.71	0.64/0.75	Fraction of pore volume that is interconnected
Displacement terms used to define the pore volume immediately surrounding a single well CO_2 Injector					
Volumetric displacement	E_V	0.16/0.39	0.26/0.43	0.33/0.57	Fraction of pore volume surrounding an injection well that can be contacted by CO_2
Microscopic displacement	E_d	0.35/0.76	0.57/0.64	0.27/0.42	Fraction of pore space unavailable due to immobile *in situ* fluids

CO_2 injection rate (q_{CO_2}, in tons/day) of each well is estimated using Darcy equation for radial flow (e.g Ahmed & McKinney 2011) of

$$q_{CO_2} = \frac{7.08\times10^{-3} kh(P_{inj} - P_{res})}{\mu_{CO_2}\left(\ln {}^{r_e}/_{r_w}\right)} / \left(6.2898 * \rho_{CO_2}\right) \quad (4)$$

for a vertical injection well, where $k, h, P_{inj}, P_{res}, \mu_{CO_2}, r_e, r_w$, and ρ_{CO_2} are formation permeability (in mD), formation net thickness (ft), injection pressure (psia), formation pressure (psia), CO_2 viscosity at injection depth (cp), radius of well spacing/boundary (ft), well radius (ft), and CO_2 density at formation condition (gr/cc), respectively.

For a horizontal injection well, the analytical model for estimating supercritical CO_2 injection rate in an anisotropic medium is given by Joshi (1991):

$$q_{CO_2} = \frac{7.08\times10^{-3} k_h h \Delta P / \mu_{CO_2}}{\ln\left[\frac{a + \sqrt{a^2 - \left(\frac{L}{2}\right)^2}}{L/2}\right] + \left(\frac{\beta h}{L}\right)\ln\left[\frac{\beta h}{2\pi r_w}\right]} / \left(6.2898 * \rho_{CO_2}\right) \quad (5)$$

where $\beta = \sqrt{\frac{k_h}{k_v}}$, and

$$a = \frac{L}{2}\left[0.5 + \sqrt{0.25 + \left[\frac{2r_{eh}}{L}\right]^4}\right]^{0.5} \quad (6)$$

with $k_h, K_v, \Delta P, L, \beta$, and r_{eh} are horizontal permeability (in mD), vertical permeability (in mD), pressure difference *(P_{inj}-P_{res})* in psia, horizontal well length (in ft), anisotropy factor (dimensionless), and radius of well spacing/boundary (lateral) in ft, respectively. The r_{eh} of Equation 6 is the same as r_e in Equation 4.

RESULT AND DISCUSSION

Determination of CO_2 source

Figure 1 presents at least five important CO_2 sources in the East Java region: Tanjung Awar-awar power plant (PP), Gresik PP, Grati PP, Paiton PP, and Jambaran Tiung Biru gas condensate field with relatively high (≈ 40%) CO_2 content. The Tanjung Awar – awar PP is located on the northern coast of East Java, within an 80-hectare area, in the Awar-Awar peninsula near the coastal city of Tuban. The PP has a power generation unit that operates two coal-fired generation units with an electrical generation capacity of 2 x 350 megawatt (MW), of which Unit I was commissioned in January 2014, and Unit II in July 2016. The Tanjung Awar-awar PP produces 104.74 tonnes/hour of flue gas from coal burning that contains an average of 22% CO_2. This creates total GHG emissions of 4,558,262.91 tons of CO_2 (year 2022 Figure) annually. The main reason for the selection of this power plant as the GHG source is based on its relatively young age and its medium power generation capacity (Weisel 2007; Finkenrath et al., 2012).

Determination of CO_2 storage

Geologically, North East Java is included in the North East Java Basin and Kendeng Basin (MEMR 2022). In the Cenozoic, the area was influenced by the relative movement of the Eurasian, Indian, and Australian Plates and experienced a complex history starting with extensional tectonics, basin subsidence, and inversion tectonics (Hamilton 1989). This basin developed from an oceanic basin in front of the Late Cretaceous subduction zone into a back-arc basin behind the volcanic arc. This basin ends in the west by the Karimunjawa Arch, extends eastward to the deep Lombok Basin, and shallows northward to the Paternoster High. Three main structural configurations can be formed from north to south: the Northern Platform, the Central Deep, and the Southern Uplift (Satyana et al., 2004).

The regional stratigraphy of the North East Java Basin can be divided into several main cycles, namely Ngimbang, Kujung, Tuban - Ngrayong, Wonocolo, and Late Miocene to Recent (Mudjiono, 2018). The Ngimbang cycle (Eocene - Oligocene) begins with a rifting process filled with siliciclastic sediments, post-rift in the form of lacustrine sediments, and continues with basin subsidence resulting in a transgression status filled with shales, massive limestone, reefal grading laterally into sandstone, siltstone, and coals. After the uplift process in the mid-Oligocene, a transgression occurred that formed the Kujung sediment (Oligo-Miocene) consisting of Kujung I, II, and III members. In the Late Oligocene, Kujung II and III were deposited. The members are composed of shales and claystone with interbedded fine-grain limestones, coal seams, and sandstones. In the Early Miocene, Kujung I was deposited as thick limestones, reefal interbedded with shale. The Tuban–Ngrayong cycle (middle Miocene) deposited thin limestones and sandstones interbedded with claystone and shales. The Wonocolo Cycle (Mio-Pliocene) deposited clay and claystone with porous limestone and sandstone lenses. The end cycle is the Late Miocene to Recent cycle (Pleistocene) that deposited sandstone, limestone, claystone, and clays (Figure 2).

Considering the suitability of the saline aquifer unit as a storage for anthropogenic CO_2, which requires lithological porosity, a depth of between 800 – 2500, and the presence of adequate overlying cap rocks, the Kujung lithological unit (Oligo-Miocene) was selected as the target of the study. For cap rocks, the overlying Tuban Formation is generally regarded as Kujung's cap rocks. This rock formation is composed of interbedded massive-poorly laminated shale, medium-hard massive carbonates with abundant corals, and fine-to-medium sandstones with silts/mudstones interbeds. The thickness of this rock formation is based on well data around Tuban that ranges from 300 to 1,500 meters (Sharaf et al., 2005).

Data processing of the Top map and thickness of the Kujung Formation in the study area produced a thickness distribution map at a depth interval of 800 – 2,500 m below subsea. The data processing follows the applicable standards in the Global Mapper-16 and Quantum GIS 3.22.5 software. The millisecond-to-depth migration process uses sound wave travel time in sedimentary rocks. Following investigations, seismic wave travel time in sedimentary rocks in the North East Java basin ranges within 1.1 - 1.2 milliseconds/meter, with the middle value of 1.15 milliseconds/meter being used in this study. The distribution of the Kujung rock formation is then split into four blocks: the North Blora Block (A1), East Blora Block (A2), South Blora Block (A3), and Southwest Lamongan Block. The isochore distribution map of this rock formation is shown by the satellite image shown in Figure 3. Calculations of the volume of each block were carried out using QGIS application. The gross rock volumes in blocks

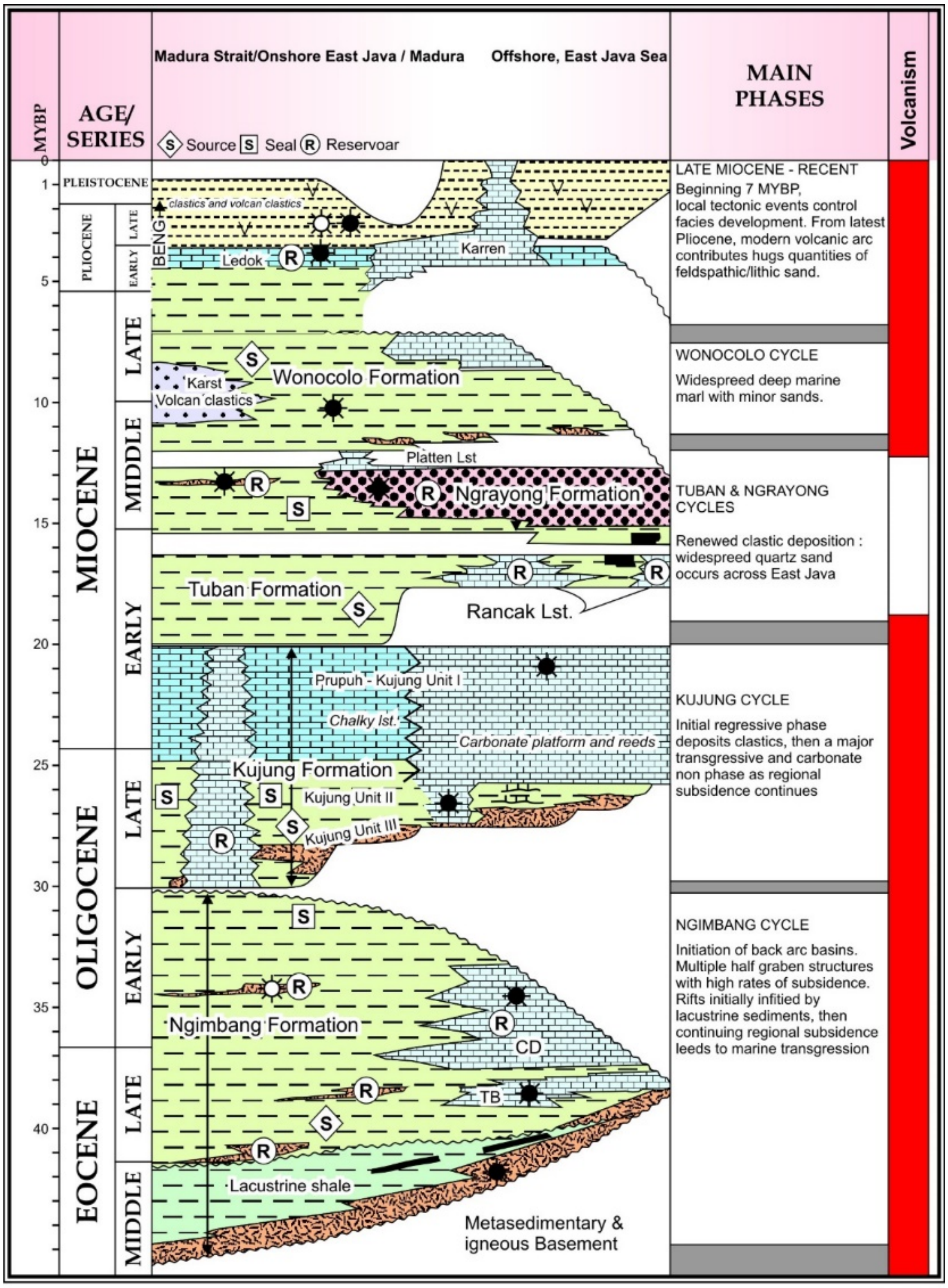

Figure 2. Regional stratigraphy of the East Java region (Mudjiono 2018)

A1, A2, A3, and B are 305 billion, 452 bilion, 199 billion, and 93 billion cubic meters, respectively, with a total gross volume of 1,053 billion cubic meters (Table 2). Analysis of the distance between stationary CO_2 sources and the Kujung formation as a geological formation for storing the CO_2 was carried out by creating a 50 km peripheral buffer around the Tanjung Awar-awar PP. Based on this analysis, the power plant appears to have the thickest part of the Kujung formation (Figure 3) within the 50-km perimeter. With depths chosen within the interval of 800 – 1800 meters subsea (m ss), the gross volume of the rock formation is estimated at around 153 billion cubic meters. This Figure is an input value for Equation 1. The area representing the gross rock volume is depicted in Figure 4.

Through a deeper review, facies distribution of the Kujung time shows extensive areas of shallow-water deposition, whereas the middle and upper Kujung shallow water is restricted to small mounds, and the remaining area is deep-water chalk and carbonate turbidites (Sharaf et al., 2005). The shallow marine carbonate facies that develops around Bojonegoro area extends northeast to the Tuban area. Around Mojokerto and the northern coast of Java, this unit exists in a west-east direction. In this shallow marine unit, mound reefs sometimes develop locally. The deep marine carbonate facies unit is found around Rembang city and extends southeast along the Ngimbang - Babat - Surabaya – Madura island axis (Figures 2 and 3).

Overlay analysis of the planned injection area and the position of oil and gas wells on the Kujung facies map shows that the JS-19 well is located in the shallow marine carbonate facies unit, and the southeast side of the planned injection area is also located in the same facies (Figure 5). With this similarity in facies, it is therefore very probable that they have similar physical lithologic properties. However, the Figure shows that not many wells are available for providing the needed data within the area for CO_2 storage, or the wells simply do not penetrate down into the Kujung Formation. Accordingly, these wells are not depicted on the map.

Based on the key well overlay map on the facies map shown in Figure 5, it appears that the JS-19, Banyu Urip – 02, and Jambaran - 01 wells are located in the Upper Kujung shallow-marine carbonate facies, while the Poleng wells are located in the Upper Kujung deep water carbonate facies. The planned injection area within the depth interval of 800 - 1800 mss is located in these two facies, to the northwest in the Upper Kujung deep water carbonates facies and to the southeast in the Upper Kujung shallow marine carbonate facies. By looking at these facies similarities, it can be assumed that both locations have developed similar types of lithology and are expected to have similar petrophysical characteristics. Provided that there is no useful petrophysics data from Banyu Urip - 2 and Jambaran - 1 wells, the data used for analogy has been taken from JS-19, Poleng DW5, and KE 41 (north of Poleng, in the same facies type) wells instead.

Petrophysics and estimation of G_{CO_2}

As in the case of other CCS studies – especially at their preliminary stage – related to geological saline aquifer for CO_2 storage, problems have been encountered mainly in the form of data shortage. The preliminary CCS study for the Tanjung Awar-awar power plant is no exception. As shown in Figures 3 through 5, the selected part of the Kujung formation is composed of the thickest part of the formation in the A2 block (Figure 3). Characteristically, no wells have been drilled with a specific task to study the selected location. This data absence leads to no static/dynamic geological models that can be constructed. Accordingly, average values were then drawn through analogy using data from other exploratory wells penetrating the Kujung Formation in the region. Figure 5 shows the selected wells from which data of the Kujung formation is available and is drawn from.

Porosity and permeability data from core analysis are available from JS-19, Poleng DW-5, and KE 41-1 wells. Figures 7 and 8 present porosity values and porosity–permeability data plot from the three

Table 2. Estimation of rock gross volumes for the four blocks of the Kujung Formation. A2 block appears to be the largest. However, only a fraction of the gross volume in the A2 block is to be used for CO_2 storage resource estimation (designated 'A2 storage area').

Block	Base area (Sq m)	Number of Pixels	Volume (cubic m)
A1	1,295,821,800	1,439,802	304,755,616,800
A2	1,634,706,000	1,816,340	451,716,304,500
A3	890,746,200	989,718	198,982,369,800
B	517,374,900	574,861	93,149,001,000
Total	**4,355,660,700**	**4,839,623**	**1,052,657,621,100**
A2 (storage area)			153,222,647,700

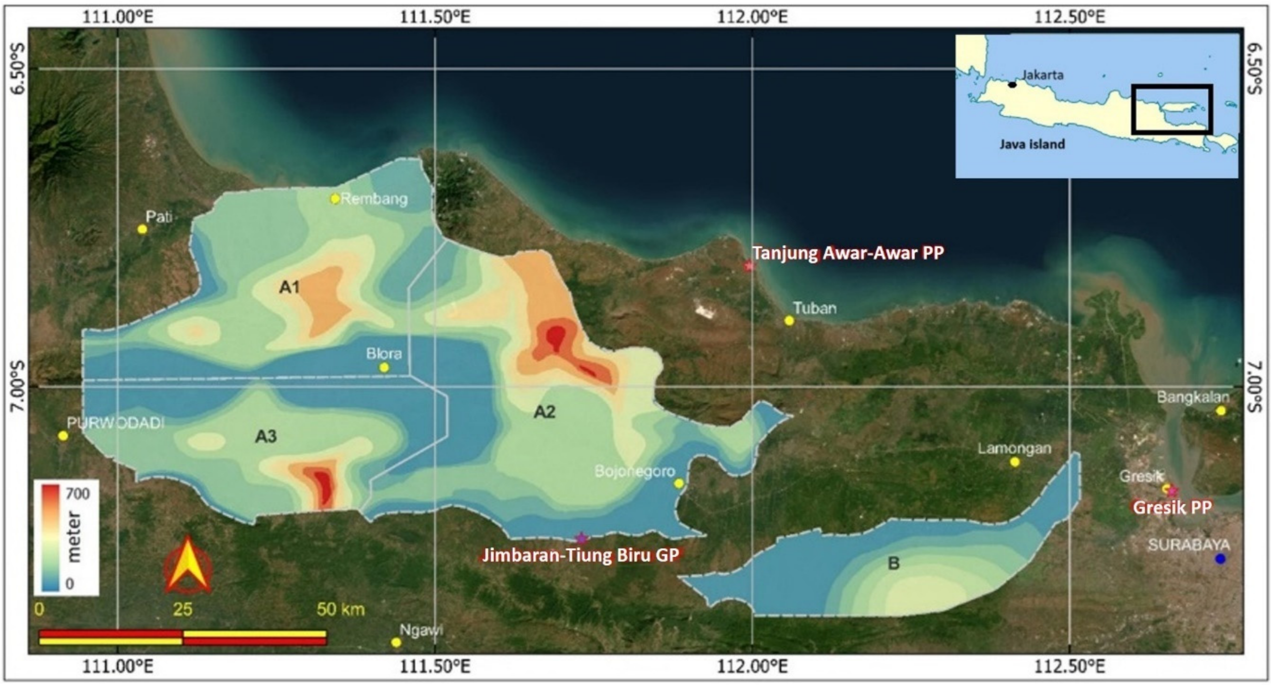

Figure 3. A satellite image along with isopach contours of the Kujung Formation. There are four areas considered as 'blocks': the A1, A2, A3, and B. Each block is characterized by the presence of thick parts designated by red and reddish areas. Tanjung Awar-awar coal-fired power plant is located roughly 14 km northwest of Tuban city.

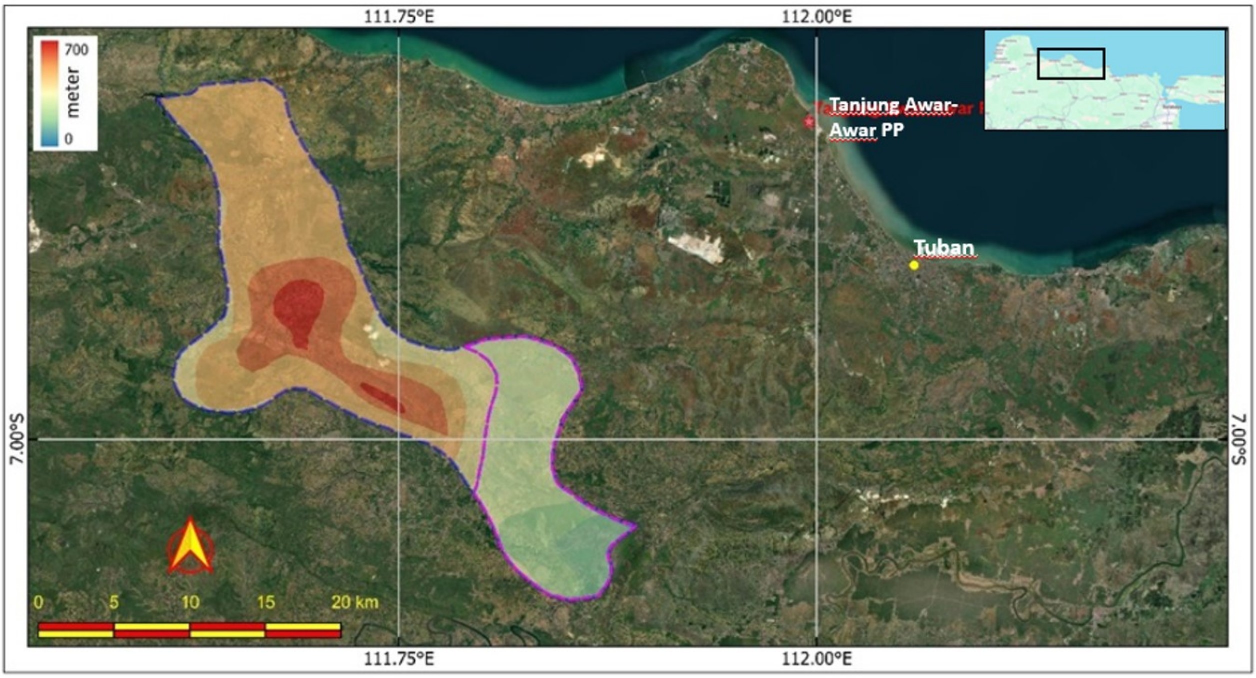

Figure 4. The thickness map (isopach) of the Kujung formation saline aquifer within the depth interval of 800 – 1,800 m ss. The site is within a 50 km radius southwest of the Tanjung Awar-awar power plant.

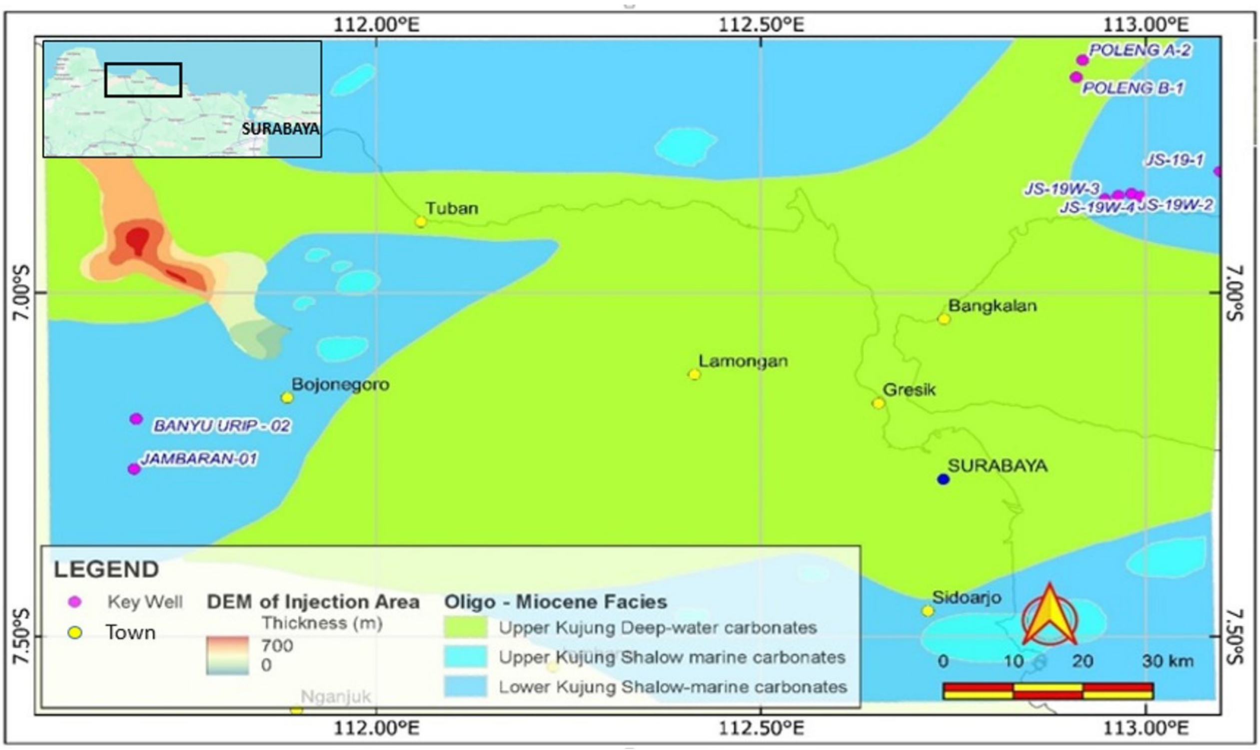

Figure 5. Overlay map depicting facies types of the Kujung Formation. The candidate CO2 storage is situated in the east of Tuban city within the depth interval of 800 – 1,800 m ss.

wells. Porosity distribution in Figure 6 shows that generally the Kujung carbonate saline aquifer has relatively low porosity values with average values of 10.2%, and with using permeability cutoff value of 0.1 mD, this roughly corresponds to around 5% porosity cutoff (Figure 7). This results in an average porosity of 12.7%. This porosity value is used in the estimation of GCO_2 in Equation 1. Using the same regression line, this 12.7% porosity corresponds to permeability of 0.6 mD. This permeability value is to be used for calculations of CO_2 injection rates.

From the petrophysical evaluation, information regarding net-to-gross $(E_{hn/hg})$ in Equation 3 can also be drawn. Qualitative evaluation on geological visual description of Jambaran-1 and Banyu Urip-02 wells provides a net-to-gross value range of 0.39 – 0.41, while quantitative core data from the other three wells of Poleng DW5, KE 41-1, and JS-19 provide a range of 0.56 – 0.74. The overall values result is therefore within a range of 0.39 – 0.74. The conservative and lowest net-to-gross value of 0.39 is adopted as the representative value for further calculations.

Table 3. Summarizes the parameters needed by Equations 1 through 3. The resulting estimated GCO_2 is **162,780,774.26** tons under the 3U (P_{10}) category in the SRMS CO_2 storage resource classification (SPE 2017).

Tanjung Awar-awar source – sink CCS scheme

With annual GHG emission of 4,558,262.91 tons (year 2022 Figure), calculations have yielded an estimated average CO_2 emission value of 10,380 tons/day. With 90% capture efficiency, this yields estimated values of 4,671 tons/day for Scenario A and 9,342 tons/day for Scenario B. Due to the power plant's relative proximity to the Kujung saline aquifer storage site, the CCS transportation scheme uses pipeline transmission. Calculations in the study using PipeSim package have resulted in the most suitable pipeline and compressor specification and operating conditions summarized in Table 4, with the ultimate objective of serving the needed injection pressure for each injection well at its injection depth. Figure 8 shows the CO_2 transmission pipeline from the Tanjung Awar-awar power plant to the storage site.

Well CO_2 injection capacity

The simulation for CO_2 transmission from Tanjung Awar-awar power plant to injection wells is essentially governed by CO_2 injection capacity of each well, both vertical and horizontal. This determines the number of injection wells needed. Estimation of injection capacity is made using Equations 4 and 5. Data that is used for the calculation is presented in Table 5, whereas the

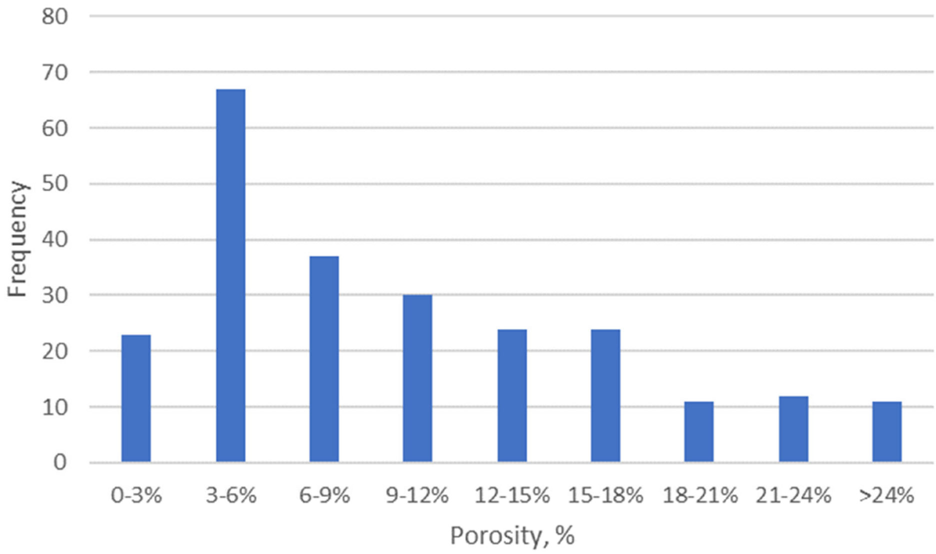

Figure 6. Distribution of porosity values from core laboratory measurements on core plugs taken from Poleng DW5, KE 41-1, and JS-19 wells.

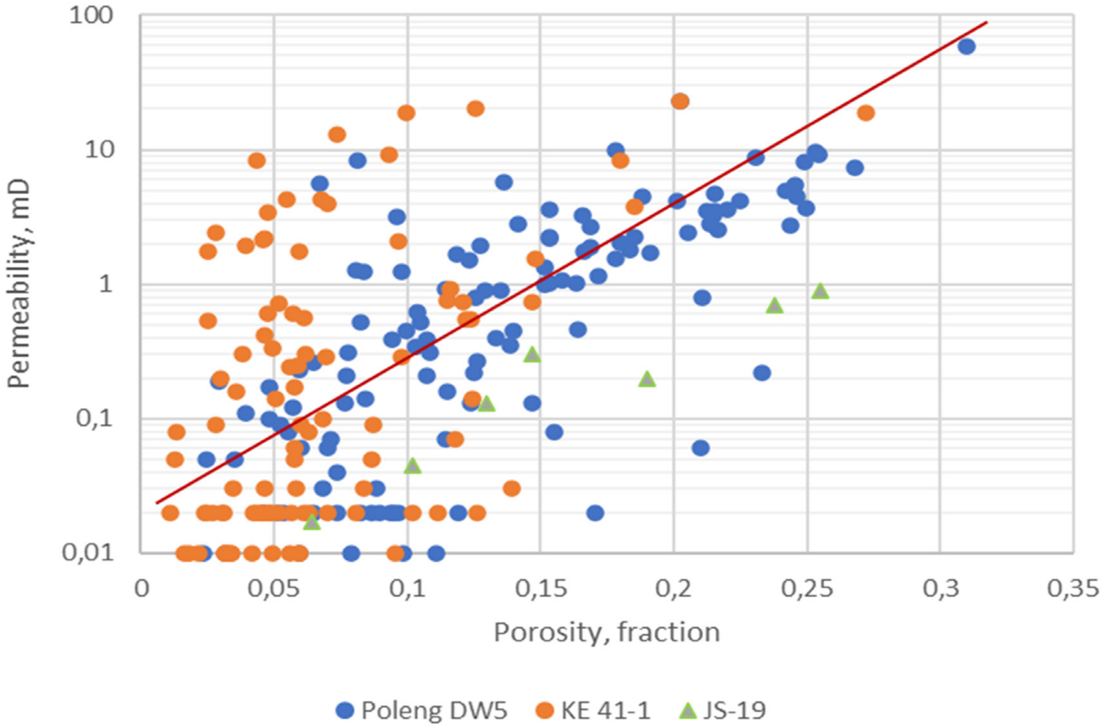

Figure 7. Plot between porosity and permeability from core samples of Poleng DW5, KE 41-1, and JS-19 wells. Permeability cutoff of 0.1 mD corresponds to porosity cutoff of around 5%, and average porosity of 12.7% corresponds to permeability of roughly 0.6 mD.

Table 3. Parameters used for determination of CO_2 storage resource (GCO_2)

Parameter	Value	Unit	Remark
$E_{An/At}$	0.6	fraction	Source: mid-value of US DOE data
$E_{hn/hg}$	0.39	fraction	Source: petrophysics evaluation
$E_{\emptyset e/\emptyset t}$	0.7	fraction	Source: mid-value of US DOE data
E_{geol}	0.164	fraction	Equation 3
E_V	0.45	fraction	Source: mid-value of US DOE data
E_d	0.345	fraction	Source: mid-value of US DOE data
E	0.0254	fraction	Equation 2
Gross rock volume	153.2	billion m^3	Part of A2 block in the Kujung carbonate formation (Figure 5)
$\emptyset$ (average)	0.127	fraction	Source: petrophysics evaluation
ρ_{CO_2}	325.1	Kg/m^3	Calculaed using relationships in Bachu (2003) @ D=1,600 – 1,700 m ss (T = 256 ºF, P = 2,500 psia)
G_{CO_2}	162.78	Mt CO_2	Equation 1

Table 4. CO_2 transmission pipeline (trunkline) specification and operating conditions.

Specification	Unit	Data	Remark
Pipeline length (real)	meter	41,710	Transmission pipeline
Pipeline ID	inch	18	Pipe grade: carbon steel
Compressor inlet pressure	psig	0.7	
Compressor outlet pressure	psig	1,400	
Compressor inlet temp.	ºF	120	
Compressor efficiency	%	95	
Compressor outlet temp.	ºF	120	

calculated injection capacities of all wells, horizontal wells only, are presented in Table 6. As presented in Table 6, a total of 8 (eight) horizontal wells have been needed to perform injections of 4,671 tons CO_2/day for 50% CO_2 capture scenario (Scenario A) and 9,342 tons CO_2/day for 100% CO_2 capture scenario (Scenario B). The two maximum injection rates are well above the 4,671 tons/day and 9,342 tons/day for Scenario A and Scenario B, respectively. This implies that the eight chosen wells with their respective locations in the isopach maps can theoretically serve the CO_2 injection scenarios. For vertical wells, following the same approach, a total of 13 wells are needed with CO_2 injection capacities ranging within 352 - 411 tons CO_2/day range is needed for Scenario A, whereas a staggering number of 29 wells with CO_2 injection capacities ranging within 294 - 411 tons CO_2/day range is needed for Scenario B. Figures 9 and 10 shows the horizontal wells' locations for Scenario A and Scenario B, respectively. From Scenario A and Scenario B, it is obvious that conceptually the Kujung formation's A2 block (G_{CO2} = 162,780,774.26 tons) can absorb the designated CO_2 injection volumes. Under the 20-year permit for carbon injection, and other assumptions in the CO_2 injection scheme described earlier, the projected CO_2 injection volumes are 34,098,300 tons and 68,189,300 tons for Scenario A and Scenario B, respectively. Regardless category of the block's storage resource (G_{CO2}), the projected CO_2 injection volumes are merely a fraction of the CO_2 storage resource in the A2 block of the Kujung Formation. This implies that, along with other parts of the formation, the Kujung Formation is suitable to serve as a saline aquifer storage for larger CCS schemes in the region under both multiple CO_2 sources and more prolonged injection schemes.

Further discussions

Results from petrophysics evaluation on the reviewed wells have shown generally that the Kujung storage is characterized by low porosity with an average of 12.7% and its low corresponding permeability of 0.6 mD. A summary of CCS experiences in saline aquifers reported by Michael et al. (2010) shows that most of the saline formations being used are of better quality petrophysically. For instance, saline aquifers used in Sleipner, SnØhvit, and Gorgon projects, which are under the status of commercial and 'injection underway', show fairly good average porosity of around 35%, 13%, and 20%, respectively. These Figures are related to representative permeability values of 5,000, 450, and 225 mD, respectively. These Figures are obviously far higher – especially in permeability – than the corresponding average/representative porosity and permeability values shown by the Kujung Formation of 12.7% and 0.6 mD, respectively. However, another summary shown by Michael et al (2010) presents that some CO_2 storage used in other projects, such as In Salah in Algeria and Alberta Basin, are characterized by much lower permeabilities of 5 mD and 1 – 413 mD, respectively. This indeed provides some optimistic view over the Kujung's feasibility for CO_2 storage. However, it is worth noting that almost all of the reported saline aquifers are sandstones lithologically, vis-à-vis Kujung's carbonate formation. As indicated by many studies (e.g Izgec et al., 2007 and Gunter et al., 2000), more interactions between the injected CO_2 and carbonates in the form of dissolution of rock minerals, transportation, and precipitation are more likely to be more intense when compared to the case of sandstone saline aquifers. This is certainly an issue to be investigated further if the Kujung carbonate formation is to be utilized for any CCS projects.

The study presented in this work is indeed essentially a volumetric balance between CO_2 source and sink only, without covering more substantial, yet more complicated, aspects such as subsurface

Figure 8. Optimized CO_2 transmission pipeline from the Tanjung Awar-awar power plant to the storage site. The line with cyan color represents Scenario A, whereas additional lines for additional wells needed in Scenario B are in green.

Table 5. Data for estimation of CO_2 injection capacity.

Parameter	Unit	Data	Remark
Top depth	meter ss	800	
Bottom depth	meter ss	1,800	
Injection depth	meter ss	1,694	
CO_2 density @ 847 m	gr/cc	0.169	Vertical mid-point to injection point
CO2 density @ 1,694 m	gr/cc	0.3205	@ injection depth
CO_2 viscosity	cp	0.02799	@ injection depth
Permeability (isotropic)	mD	0.6	@ average porosity above cutoff
Wellbore radius, r_w	ft	0.583	Inner radius
Reservoir radius, r_e	ft	3,280	Spacing for an injection well
Injection pressure, P_{inj}	psia	3,000	@ injection depth, 1.2 x P_r (referring to Wang et al, 2016) to avoid caprock fracturing
Reservoir pressure, P_{res}	psia	2,500	@ injection depth
Wellhead pressure	psia	2,610	Used in CO_2 pipeline/flowline simulation
Horiz. section length, L	ft	3,280	All wells

Table 6. Results of well CO_2 injection capacity (horizontal wells only) for both Scenario A (50% CO_2 capture) and Scenario B (100% CO_2 capture).

Well	Coordinates	Net vertical thickness (ft)	Max injection rate capacity (tons CO_2/day)	Remark
Scenario A				
B-39	Lat: -6.9065 Long: 111.7054	918.5	1,271	
B-49	Lat: -6.9335 Long: 111.6899	918.5	1,271	
C-81	Lat: -6.9694 Long: 111.7521	852.9	1,231	
C-88	Lat: -6.9784 Long: 111.7365	918.5	1,271	
Total max. injection rate (Scenario A)			5,046	Captured CO_2 = 4,671 tons/day
Scenario B (Scenario A + 4 wells below)				
A-12	Lat: -6.8257 Long: 111.6588	656.1	1,084	
A-26	Lat: -6.8706 Long: 111.6743	721.7	1,138	
B-38	Lat: -6.9065 Long: 111.6743	852.9	1,231	
B-61	Lat: -6.9514 Long: 111.6588	852.9	1,231	
Total max. injection rate (Scenario B)			9,731	Captured CO_2 = 9,342 tons/day

modeling involving reservoir static and dynamic models, geomechanics, and other scientific areas like geochemistry. These 'fancy' approaches are certainly needed for ensuring various CCS aspects like injection scenarios, operational guidelines, and storage safety. Nonetheless, these approaches require sufficient input data, both in quality and in quantity. For Indonesia's 21 producing basins (mostly in western Indonesia), data acquisitions at both well and field scales within the basins are arguably abundant, but potential saline aquifers are usually located beyond the areas specifically designated as oil/gas working areas. Let alone potential saline aquifers in other sedimentary basins with status of 'non-producing' or 'unexplored'. For those locations, the most likely data availability is merely from gravity and/or magnetic surveys, plus probably a few 2-D seismic lines with one or two dry exploratory wells. This condition is certainly insufficient for proper, especially project-based, CCS studies. With the onset of intensive CCS activities in the Southeast Asia region in general, and in Indonesia in particular, this fact poses huge challenges not only in economics and regulatory fields but also in more technical aspects like preparation for storage resources, especially when they are directed to act as regional CCS/CCUS hubs. Under the light of these challenges, it is hoped that the results of this study may serve as an accelerator to deeper and more thorough studies, which in turn will require more appropriate data through well-designed data acquisition activities.

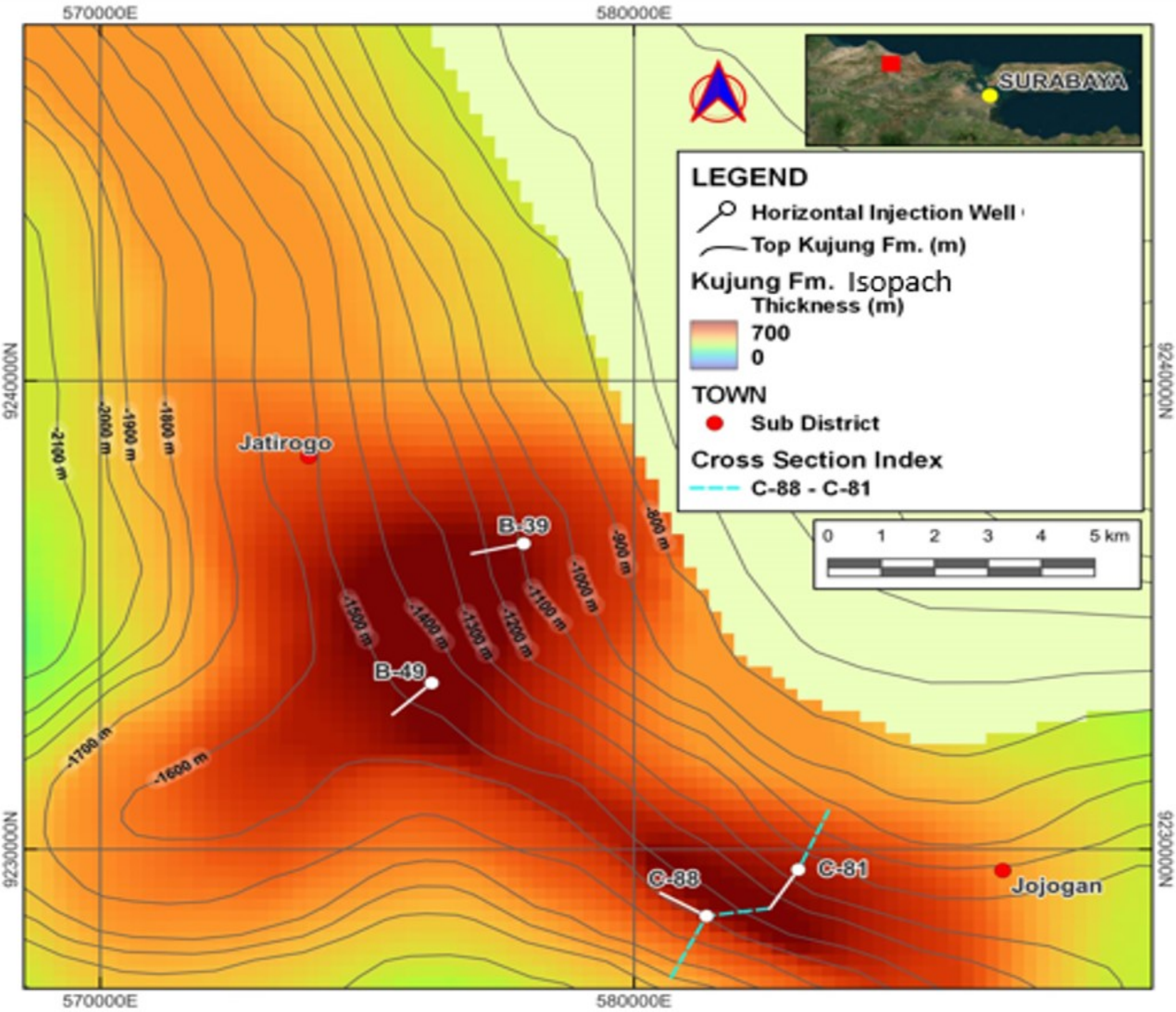

Figure 9. The four CO_2 horizontal injection wells in Scenario A.

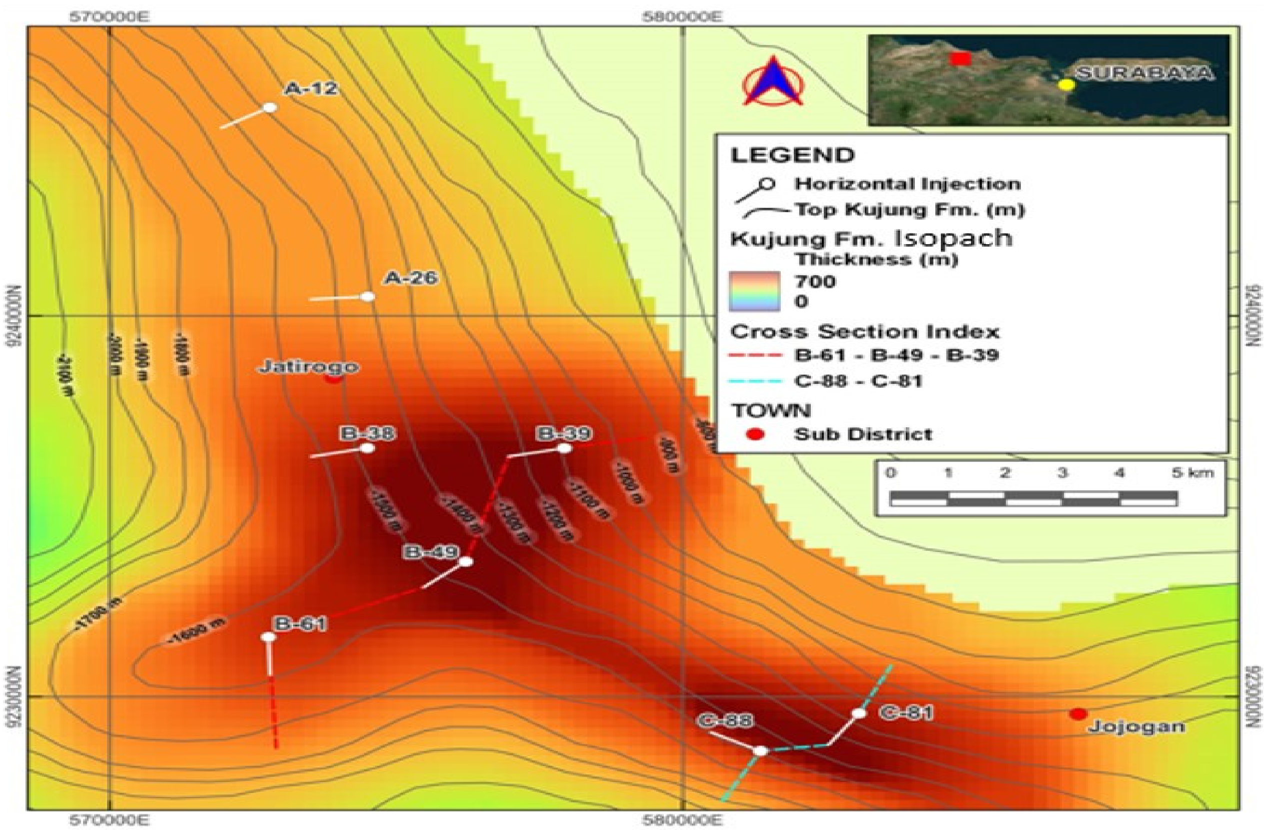

Figure 10. The eight CO_2 horizontal injection wells in Scenario B.

CONCLUSION

The CO_2 storage resources of the saline aquifers in the carbonate Kujung Formation in the North East Java and Kendeng basins in the East Java region appear to be sufficient to support carbon capture and storage (CCS) activities in the East Java region, Indonesia. This is shown by the formation's A2 block's capacity, with its CO_2 storage resource (G_{CO2}) estimate of 162.78 $MtCO_2$, to cope with 9,342 tons CO_2/day emission from Tanjung Awar-awar's 2 x 350 MW coal-fired power plant for 20 years, and beyond, under certain assumptions using a set of well-placed horizontal wells. Furthermore, the block's storage resources, plus storage resources of other parts of the formation, have shown that the Kujung Formation can serve as a saline aquifer CO_2 storage for regional CCS activities under multi-CO_2 sources and prolonged injection schemes, and therefore may help significantly in the efforts to achieve net-zero greenhouse gas emissions in the region. This essentially CO_2 source – sink volumetric balancing study also serves as an example of a macro-preliminary CCS study for a hard-to-abate medium-size coal-fired power plant involving a saline aquifer in nearby geological locations. Nevertheless, the absence of sufficient and proper data for this study deserves serious attention, especially when this study is to be followed up further by more detailed and realistic ones.

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GLOSSARY OF TERMS

Symbol	Definition	Unit
a	Anisotropy parameterin Joshi model	dimensionless
β	Anisotropy factor	dimensionless
ΔP	Differential pressure ($P_{inj} - P_{res}$)	psia

μ_{CO_2}	CO_2 viscosity at injection depth	centipoise (cp)
ρ_{CO2}	Density of CO_2 at formation condition	gr/cc
Ø	Porosity, a part (pore space) of rocks that can be filled with fluids	fraction
A	Investigated area	sq-m
CCS	Carbon capture and storage	-
CCUS	Carbon capture, utilization, and storage	-
CCUS-EGR	Enhanced gas recovery (EGR) as a means of CCUS	-
CO_2	Carbon dioxide	-
CO_2-EOR	Enhanced oil recovery scheme through the use of field-scale CO_2 injection	-
CSLF	Carbon Sequestration Leadership Forum	-
DEM	Digital elevation model	-
E	Storage coefficient	fraction
E_d	Portion of the pore space occupied by CO_2 as a result of microscopic (pore scale) displacement	fraction
$E_{\emptyset e/\emptyset t}$	Formation total porosity having interconnection	fraction
E_{geol}	Portion of pore space available for storage	fraction
$E_{An/At}$	Formation area suitable for storage	fraction
$E_{hn/hg}$	Net-to-gross thickness ratio	fraction
E_V	Portion of the pore space occupied by CO_2 as a result of macroscopic displacement	fraction
GHG	Greenhouse gas	-
GIS)	Geographic information system	-

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