Potential of CCS in East Kalimantan’s Coal-Power Sector for Achieving Net-Zero Emissions

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Abstract: Coal-fired power plants are a foremost source of greenhouse gas emissions in the energy sector. Current technology on Carbon Capture Storage (CCS) retrofit is a feasible mitigation strategy to support emission reduction in fossil-based power plants. This technology will reduce greenhouse gas emissions massively compared to other technologies. This study aims to analyze the potency of CCS retrofit on coal-fired power plants in East Kalimantan. Source-sink matching was mapped based on the close distance of 8 power plants and nearby oil and gas fields as sinks. The result showed that total of 3,228,801 tons of CO2 emissions per year can be retrofitted through the use of oil and gas fields within a 50 km radius with a storage capacity of 1,790.53 million tons. However, only one power plant is considered the best target for retrofitting CCS with total CO2 emissions of 1,221,319 tons/year capable of being stored with capacity storage of 447.20 million tons (radius 75 km). This study will be a guide for determining coal-fired power plants in East Kalimantan that are potentially suitable for CCS retrofit to support net zero emission policy by 2060.

Keywords: Carbon Capture Storage; fossil-based power plant; CO_2 source-sink matching; depleted oil and gas fields.

1. Introduction

Indonesia is anticipating a Net Zero Emission (NZE) by 2060, and to achieve this objective, there is an ongoing shift from fossil energy to new renewable sources, known as blue and green energy[1)]. The transition is still slow, which means fossil energy will still dominate in the next few years[2)]. Many power plants rely on coal due to its cost-effectiveness and abundant availability in several countries[3)]. However, the largest contributor of greenhouse gas (GHG) emissions tends to be Coal Fired Power Plants (CFPPs)[4)]. Preliminary research stated that the average emissions from CFPP are 1.24 tons of CO_2/MW, which is relatively high[5)]. Five priority emission categories GHG (CO_2, $PM_{2.5}$, SO_2, NOx, Hg) released into the air along the coal power plant supply chain[6)]. The adoption of relevant efforts is necessary to reduce these emissions and prevent early retirement of future CFPP construction.

As CFPP have considerable lifespan, Carbon capture and storage (CCS) retrofit technology is considered extremely prospective for storing the generated CO_2[7)]. CCS is a moderation technology that systematically comprises three sequential activities ranging from capturing CO_2 from diverse sources, transporting and injecting it into storage sites and geological formations. These three activities enable the storage of emissions in depleted oil and gas reservoirs, includes saline aquifers [8)].

The implementation of CCS incurs considerable costs, focusing on the need for in-depth research to identify the most optimal and applicable design. The important parameters for assessing CCS retrofit potential at CFPP comprise technical, economic, and social feasibility[7)]. Its successful implementation relies on three main potentials, namely theoretical, technical, and cost-effective, which include realistic, as shown in Fig.1[7)]. The practical selection is guided by technical and economic feasibility, with additional requirements, for societal acceptance and compliance to existing laws[7)].

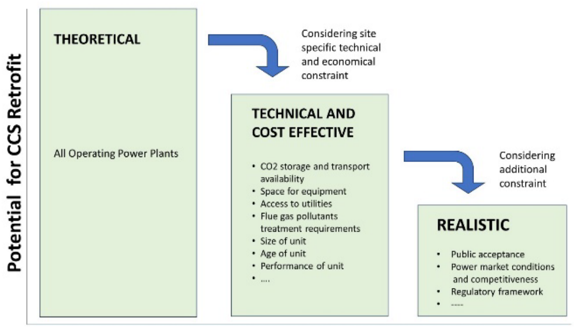


Fig.1: Potential for retrofit CCS.

Whether applied in retrofitting CFPP or other related projects, CCS technology is recognized as an effective method to control carbon emissions. The retrofitting of CFPPs with CCS has been proven to be a practical solution. A basic case study stated that a minimum carbon price of \$140/ton of CO_2 is required to promote power plant owners to pursue CCS retrofitting from fossil fuel-based power plants[9]. This retrofit approach, known as carbon capture utilization and storage (CCUS), is an effective solution for controlling emissions from existing and planned fossil fuel power plants. This is because a significant portion of the global power fleet is unlikely to shut down within timeframes that meet climate targets. Meanwhile, approximately one-third of all coal-fired power capacity is less than ten years old, specifically in Asia[10].

1.1 Previous studies of capacity criteria and age of coal-fired power plants

Several publications, including detailed research by the IEA Greenhouse Gas Implementing Agreement, have focused on the analysis of retrofits in CFPP (IEAGHG, 2011). The present research offers a lot of technical knowledge, proving highly beneficial in understanding the complexities of CCS retrofits. The global energy scenario shows the critical nature of CCS retrofits for achieving significant emissions reductions, such as building new power plants[11]. However, most previous research is in line with a 2005 assessment by the International Panel on Climate Change (IPCC) that retrofitting existing power plants with CO_2 capture installations requires higher costs and significantly reduces overall efficiency compared to building new power plants equipped with similar devices. To minimize site-specific constraints, it was proposed that factories or power plants should be equipped with CCS capture devices from the beginning, presenting a crucial option to avoid locking in further CO_2 emissions from power plants to be built in the near future[12]. A detailed analysis conducted by the Electric Power Research Institute (EPRI) during a CCS retrofitting workshop held at Massachusetts Institute of Technology (MIT) in 2009 reported that boilers with a capacity of 300 MW or greater and less than 30 years old are the most feasible candidates for cost-effective carbon capture retrofits[13]. The U.S. National Energy Technology Laboratory conducted detailed research on the potential retrofit of CCS in coal-fired power plant fleets across the United States (NETL, 2011)[14]. NETL also established specific criteria to identify power stations unsuitable for retrofitting with CO_2 capture devices. These criteria include plants not currently in operation, those with a capacity of less than 100 MW, facilities with a reported heat rate in 2008 greater than 12,500 Btu/kWh (higher heating value, HHV), or equivalent to approximately 29% efficiency (lower heating value, LHV), and power stations lacking a designated CO2 storage area within 25 miles (40 kilometers). Based on the results from previously reviewed literature, an investigation has been launched using the WEPP database to comprehensively define the profile of the power plant across various pertinent aspects[7] as shown in Table 1.

Table 1. Profile of the power plants in various pertinent aspects

Power Generation Capacity (MW)	Age, the year of the first operation (years)	Performance level (Vapor quality parameters)
• up to 100 MW • 100-500 MW • >500 MW	• 0-5 • 5-10 • And so on	• Sub critical • Super critical • Ultra-supercritical

Retrofitting all coal-fired power plants with CCS is important for reducing CO_2 emissions. However, the selection of suitable plants must be in line with technical and economic feasibility, community acceptance, and regulatory compliance. Meanwhile, the initial construction of power plant fleets should have been designed to incorporate CCS-ready features, such as integrating CO_2 capture equipment, to minimize energy penalties during the subsequent retrofitting process.

1.2 Implementation of CCS in some countries

CCS projects have been carried out in several countries, including Canada, Norway, Japan, and the People Republic of China. The Global CCS Institute reported that as of 2020, operational projects had captured approximately 40 million tons of CO_2 emissions annually, while an additional 50 million tons per year were being developed[15]. Despite the implementation of the CCS projects across the globe, with an annual CO2 of approximately 38 billion tons emitted globally[16], CCS projects were expected to capture only a minute fraction of about one-thousandth by 2020.

The Alberta Carbon Pipeline (ACTL) project, a groundbreaking initiative valued at CAN\$1.2 billion, is the most significant CCS system in the world. This project features a 240 km pipeline designed to collect industrial CO_2 emissions from the Agrium fertilizer plant and the North West Sturgeon oil refinery in Alberta. The collected carbon dioxide is then used for enhanced oil recovery

(EOR) projects and permanent storage at the Clive oil reservoir, which has a capacity of 14.6 million tons of CO_2 per year[17]. Additionally, the CCS Quest project operates in the Athabasca oil sands/heavy oil production at the Scotford Upgrader near Alberta, where CO_2 is injected into a porous rock formation called the Cambrian Sands Basin. From 2015 to 2018, the project successfully stored 3 million tons (Mt) of CO_2 at a rate of one million tons per annum (Mtpa)[18]. Other significant projects include the Great Plains – Canada synthetic fuel plant retrofitting, injecting 0.4 Mtpa and 2.4 Mtpa into the Midale and Weyburn fields, respectively, contributing to a total injection capacity of 2.8 Mtpa with more than 30 Mt of CO2 injected between 2000 and 2018[19]. In Japan, a large-scale CCS demonstration project is ongoing in the Tomakomai area of Hokkaido. This project aims to show the feasibility of a full-cycle CCS system, from CO_2 capture to injection and storage. Furthermore, over one hundred thousand tons per year or more of CO_2 are captured, injected, and stored in the seabed salt aquifer at Tomakomai Port. The injection process into the Moebetsu Formation, a sandstone layer, was successful, with 170,000 tons of CO_2 already injected as of April 24, 2018. This project aims to inject a total of 300,000 tons for three years[20]. The Norwegian Sleipner, a fully operational offshore gas field with CO_2 injection since 1996, separates this gas from that of production and injects it into the Utsira saline aquifer (800–1,000 m below the seabed) above the hydrocarbon reservoir zone[21]. The large size of the aquifer allows for the storage of approximately 600 billion tons of CO_2. Moreover, CNOOC Ltd. has started a carbon capture and storage project at the Enping 15-1 oil field complex in the Pearl River Mouth basin of the South China Sea. The scheme includes building facilities to capture relatively 300,000 tons of CO_2 annually, with plans to store approximately 1.46 million tons in reservoirs located 190 kilometers southeast of Hong Kong offshore, at a water depth of 80 meters[22].

1.3 CCS Prospects in East Kalimantan

Several studies on CCUS-EOR have been conducted in Indonesia, specifically in Sumatra and Java. A comprehensive screening of oil fields in South Sumatra showed 18 suitable for immiscible CO_2 injection, 77 for miscible injection, and 7 for not meeting CO_2 injection criteria. A comprehensive screening of oil fields in South Sumatra revealed 18 suitable for immiscible CO_2 injection, 77 miscible ones, and seven failed to meet the stipulated criteria. The anticipated increase in oil production from CO_2-based enhanced oil recovery (CO_2-EOR) was estimated at approximately 480.5 million STB. Meanwhile, the estimated total CO_2 storage was approximately 92 million tons, with 70 million tons from the production process till the URR (Ultimate Recoverable Reserve) was completed and an additional 22 million tons from the EOR procedure[23]. Source and sink matching investigations in Indonesia have identified 24 potential oil fields for CO_2-EOR, selected from mature ones with a total remaining oil in place of 4.3 billion barrels. Primarily located in South Sumatra, West, and East Java, these fields are part of an initiative that includes 176 sources emitting approximately 170 million tons of CO_2 yearly. The matching process, conducted within a radius of 100 and 200 km from the CO_2 sources, has strategic implications for the region[24]. Furthermore, research have also been carried out to explore the potential for CCUS EOR in the North-West Java Basin. Source and sink matching around CO_2 emission sources like the Indramayu and Cirebon power plants and Balongan oil refinery, including the cement industry, were conducted at a radius of 50 and 100 km. Within a 50 km radius, depleted oil fields showed the capacity to absorb between 287 and 380 million tons of CO_2, yielding an additional 575 and 1,150 million stock tank barrels (MMSTB) of oil. Expanding the radius to 100 km, all depleted oil fields showed the capacity to absorb between 633 and 835 million tons of CO_2, leading to an additional 1,265 and 2,530 MMSTB of oil[25]. Research has been conducted on techniques used for tar abatement, CO2 capture, and potential areas for CO2 utilization[26].

As part of the plan to relocate the capital of Indonesia to East Kalimantan, the region will certainly need an increased supply of electrical energy. Currently, power generation in East Kalimantan is predominantly coal-based. With thirteen sedimentary basins in Kalimantan[27], the area holds substantial potential to serve as a CCS storage site. Sedimentary basins of Kalimantan are prolific for petroleum and coal deposits. One of the basin, Kutei Basin, have been producing oil since the late 1800s and remains to be one of the most prolific basins in Indonesia[28]. Moreover, the numerous oil and gas fields in East Kalimantan, already in depleted conditions, also have great potential for CO_2 storage[29], as shown on Fig. 2. The term depleted condition refers to a state where the oil and gas fields have lost natural pressure, resulting in extremely low or non-existent productivity levels. This situation shows that the East Kalimantan province is an ideal area for implementing CCS initiatives.

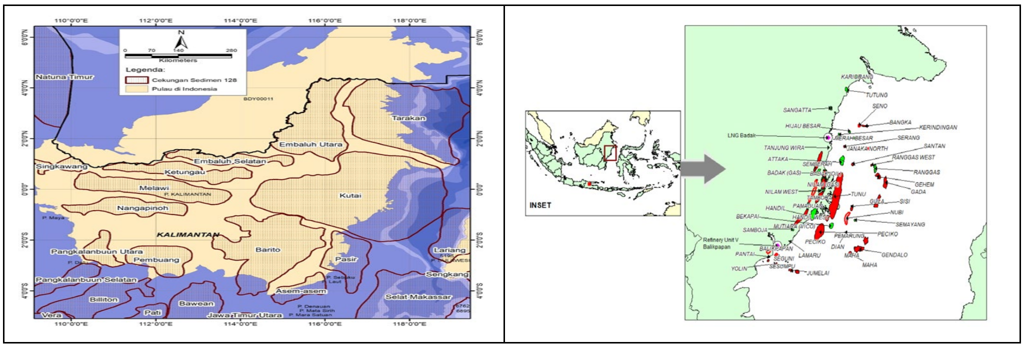


Fig. 2: Distribution of sedimentary basins and oil and gas fields in East Kalimantan (left), and oil (green) and gas (red) fields in East Kalimantan (right).

This study aimed to examine the feasibility of implementing CCS retrofit in power plants located in East Kalimantan. This location was chosen to support the capital relocation plan of the government and due to the abundance of sedimentary basins containing depleted oil and gas fields. These factors collectively made this province a promising location for applying CCS, enabling the storage of a significant portion of GHG emissions generated by industrial activities in the region.

2. Methodology

In evaluating the potential for implementing CCS retrofit at CFPPs in East Kalimantan, the following steps were adopted: 1) establishing an inventory of existing coal-fired power plants. This data included relevant information such as location, production capacity, age of the plants, land area, and annual GHG emissions, 2) calculating the CO_2 storage capacity estimation in oil and gas fields in east Kalimantan, 3) mapping carbon dioxide sources from coal-fired power plants in the region using a Geographic Information System (GIS)[30]. This mapping exercise not only identifies emission sources but also serves to illustrate potential storage locations. The process includes source-sink matching between CO_2 emission sources from coal-fired power plants and geological formations capable of its storage[24], and 4) using specific criteria, such as electricity capacity and age of the coal-fired power plants, to identify the most promising candidates for CCS applications. Additionally, estimating the storage capacity and conceptualizing pipeline network from selected CFPPs to the nearest oil and gas fields.

2.1 Coal-fired power plants inventory

The inventory of existing coal-fired power plants in East Kalimantan was aimed to systematically collect relevant data. This information includes plant location, production capacity, age, land area, and total annual GHG emissions.

2.2 Estimated CO_2 Storage Capacity

This research estimated the CO_2 storage capacity of oil and gas fields in East Kalimantan using a production-based approach proposed by Bachu et al. (2007) [31], as stated in the following equations,

$$\textit{Oil reservoir } CO_2 \textit{ Storage Capacity} = OOIP \times RF \times Bo \times CO_2 \textit{ density} \quad (1)$$

$$\textit{Gas reservoir } CO_2 \textit{ Storage Capacity} = OGIP \times RF \times Bg \times CO_2 \textit{ density} \quad (2)$$

where *OOIP* is the original oil in place, *OGIP* is original gas in place, *RF* is recovery factor (fraction/factor of oil/gas that can be obtained or produced relative to *OOIP/OGIP*, fraction), *Bo* is oil formation volume factor (ratio of oil volume in reservoir and volume at surface conditions, units RB/STB), and *Bg* is gas formation volume factor (ratio of volume of gas in reservoir and volume at surface conditions, units of cu-ft/SCF). In contrast, *CO_2 density* is considered concerning supercritical conditions, expressed in kg/m3. In this study, CO_2 storage capacity was estimated in two cases with both containing the estimated ultimate recoverable reserve (URR) and forecasted total production amount in 2060, respectively. The calculation of CO_2 storage capacity is dependent on Voidage replacement, while the fluid exiting the reservoirs is the same as the stored gas, assuming there is no injection or water production.

2.3 Source and sink matching

The source and sink matching of CO_2 from CFPP in depleted oil and gas fields was analyzed using a geographic information system (GIS). The GIS adopted the World Geodesion System-84 (WGS 84) – EPSG (European Petroleum Survey Group) 4326 geographic coordinate system in latitude and longitude as the projection reference framework. Each power plant location is considered as a single source with multiple potential sinks. Vector data operations were used to create radial buffers at distances of 50 km, 75 km, and 200 km from the center of CO_2-producing sources. These buffers enabled the identification of oil and gas fields existing within each specified area. A vector data operation is performed to generate a distance matrix to determine the direct distance between the source and storage. Technical analysis was then conducted by considering the fixed volume of CO_2 emissions produced by each coal-fired power plant and the available storage capacity within the oil and gas fields at specific distances. Additionally, the analysis considers the duration of the storage program to assess its feasibility for long term or permanent implementation.

2.4 Classification of power plants selection

This research focused on two main factors from the three criteria mentioned previously to monitor the potential implementation of CCS in CFPP7). The selected criteria are the capacity and the age of the power plants. Using these two-dimensional criteria, coal-fired power plants in East Kalimantan that have CCS retrofit potential, especially those with less than 10 years and with a power generation capacity exceeding 200 MW, was selected.Apart from that, the data obtained from the selected power plants amounted to eight units.

3. Results and Discussion

3.1 CFPPs inventory

The outcomes of the initial screening for potential CCS retrofit in CFPPs in East Kalimantan are shown in Table 2. The identified CFPP units are labeled with the nomenclature PP followed by numbers 01 to 08, while the geographical locations are shown in Fig. 3.

Table 2. Identification result of CFPPs in East Kalimantan.

Power Plants	Nomen clature	Age	Capacity (MW)	Year of emission	Emission (CO_2e ton/year)
Power Plant 01	PP 01	4	14	2020	102,179.9
Power Plant 02	PP 02	6	220	2020	1,221,319.4
Power Plant 03	PP 03	9	30	2019	252,220.0
Power Plant 04	PP 04	12	15	2019	211,199.0
Power Plant 05	PP 05	15	60	2019	152,064.0
Power Plant 06	PP 06	19	21	2021	186,393.8
Power Plant 07	PP 07	20	110	2019	1,043,206.1
Power Plant 08	PP 08	26	60	2021	60,219.4

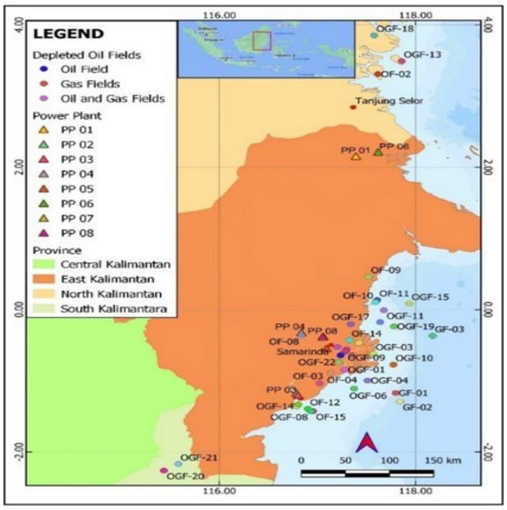


Fig. 3: The location of CFPP and oil and gas depleted in east Kalimantan

3.2 CO2 storage capacity estimation

The estimated CO_2 storage capacities of 22 oil fields with gas reservoirs (OGF), 17 oil fields (OF), and eight gas fields only (GF) in East Kalimantan are shown in Tables 3 to 5. Cases 1 and 2 are estimates using the conceptual maximum recovery factor or URR and RF forecasted for individual fields by the year 2060, respectively.

Table 3. Results of estimated storage capacity of depleted oil gas fields (OGF).

OGF Code	Field	Storage Capacity of CO_2 (Mton) Case 1	Case 2
OGF-01	Handil	355.20	358.10
OGF-02	Attaka	317.82	323.05
OGF-03	Tunu	715.29	836.33
OGF-04	Bekapai	77.69	77.69
OGF-05	Nilam	284.80	290.50
OGF-06	Peciko	60.68	62.25
OGF-07	Badak	814.96	822.24
OGF-08	Sepinggan	12.80	13.42
OGF-09	Tambora	185.49	186.65
OGF-10	Sisi/Nubi	121.35	154.61
OGF-11	Serang	50.44	39.16
OGF-12	Kutai Lama N.	10.06	8.14
OGF-13	Bunyu+Nibung	20.72	21.14
OGF-14	Yakin C/W/N	4.15	4.45
OGF-15	West Seno	35.16	35.35
OGF-16	South Mahakam	50.26	93.22
OGF-17	Semberah	80.31	81.22
OGF-18	Sembakung	14.28	13.16
OGF-19	Santan	30.20	30.19
OGF-20	Warukin South	2.67	2.00
OGF-21	Tapian Timur	1.89	1.80
OGF-22	Pamaguan	4.23	4.51
Total		**3,250.45**	**3,459.18**

Tabel 4. Estimated storage capacity of depleted oil fields (OF)

OGF Code	Field	Storage Capacity of CO_2 (Mton)	
		Case 1	Case 2
OF-01	Louise	28.49	28.00
OF-02	Pamusian	7.53	7.49
OF-03	Samboja	5.29	5.23
OF-04	Mutiara	3.80	4.61
OF-05	Muara	3.42	3.03
OF-06	Beras	3.38	3.37
OF-07	Anggana	2.95	2.89
OF-08	Mahoni	2.58	2.72
OF-09	Sangatta	2.12	1.97
OF-10	Melahin	1.19	1.26
OF-11	Kerindingan	0.86	0.96
OF-12	Seguni	0.58	0.66
OF-13	T.Una	0.52	0.52
OF-14	Lampake	0.40	0.41
OF-15	Sedandang	0.30	0.30
OF-16	Bangkirai	0.17	0.16
OF-17	Sambutan	0.09	0.02
Total		**63.67**	**63.60**

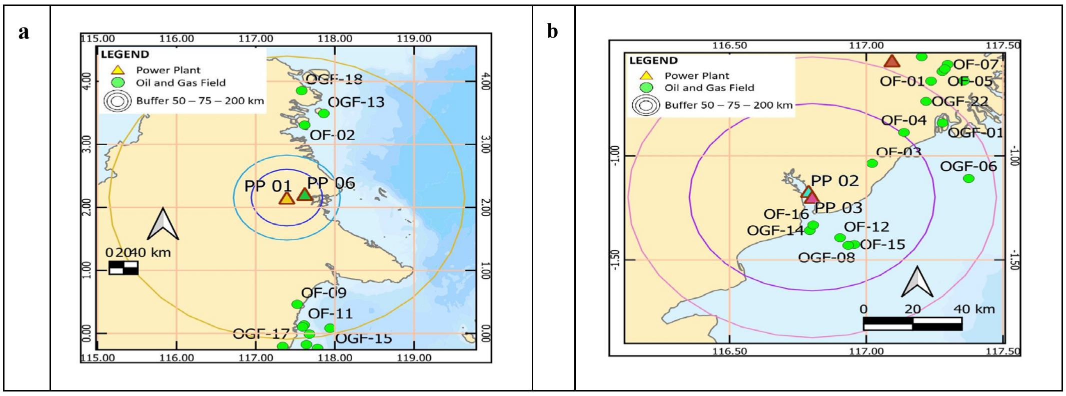
Tabel 5. Estimated storage capacity of depleted gas fields (GF)

OGF Code	Field	Storage Capacity of CO_2 (Mton)
		Case 1
GF-01	Jangkrik	35.61
GF-02	Gendalo	60.65
GF-03	Gehem	63.46
GF-04	Jangkik NE	29.02
GF-05	Gandang	1.41
GF-06	Tapa + Teritip	28.79
GF-07	Bunyu Tapa	24.78
GF-08	Sesayap	26.79
Total		**270.51**

The results of both Cases 1 and 2 are highly consistent, allowing interchangeability in this study. Based on the data analysis, the power plants emit approximately 3.23 million tons of CO_2 equivalent (CO_2e) annually. The total CO_2 storage capacity for the 22 oil and gas fields is 3,250.45 and 3,459.18 million tons for Cases 1 and 2, respectively. The total storage capacity for the 17 oil fields is 63.67 and 63.60 million tons for Cases 1 and 2, respectively. The eight gas fields have a total storage capacity of 270.51 million tons in Cases 1. In subsequent years, there is sufficient capacity to accommodate CO_2 emissions from the power plants, compared to 3.23 million tons currently generated annually. The selection of CO_2 injection can prioritize CFPPs with larger capacities located closest to oil and gas fields. Further investigations need to be carried out along with clustering, source, and matching to estimate distances between the oil and gas fields as well as CFPP.

3.3 Clustering and source-sink matching

Source-sink matching includes defining the power plant locations as CO_2 sources (source point) and identifying the midpoint of depleted oil and gas fields as the storage center (sink). A map of each power plant location in relation to the storage candidate oil and gas fields in the three buffer areas is shown in Fig. 4. The mapping of CO_2 sources from power plants in East Kalimantan allows for its recognition and the creation of networks in candidate oil and gas fields. Eight power plants were mapped with network boundaries in the form of buffers, each with a radius of 50 km, 75 km, and 200 km. Clustering was established within this network to determine the locations and potentials of the nearest oil and gas fields from certain power plants serving as CO_2 sources, the radial distances cover various candidate target fields. This prepared map, aimed at achieving NZE objectives, serves as a reference for further detailed preparations and source-sink network design. While potential overlap in radial buffer zones between power plants in the oil and gas fields may present the risk of double counting in total storage capacity, measures have been taken to avoid this problem, and the overlapping estimated storage capacity was also considered.



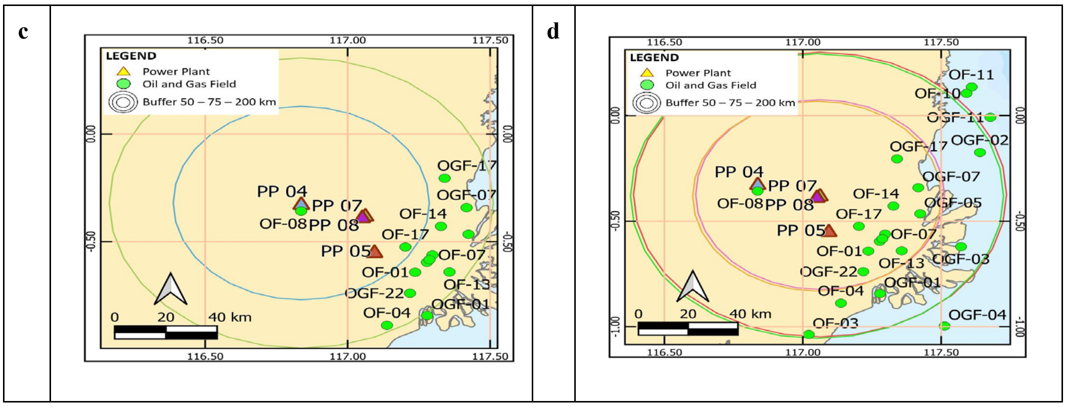


Fig. 4: CO_2 source map of (a) Power plant (PP) 01 and 06; (b) PP 02 and PP 03; (c) PP 04, PP 05, PP 07 and PP 08 for radius 50 km and 75 km; and (d) PP 04, PP 05, PP 07 and PP 08 for radius 75 km and 200 km.

The configuration results realized from the eight power plants, the number of potential nearby oil and gas fields within 50 km, 75 km, and 200 km radius and its corresponding CO_2 storage capacities are shown in Table 6. This table offers a clear representation of the gross aggregated CO_2 storage capacity available to the power plants. For PP 01 and PP 06, there were no nearest oil and gas fields found within a 50 km and 75 km radius. Meanwhile, within a radius of 200 km, only four oil and gas fields, namely the OF02, OF09, OGF13, and OGF18, were identified with a total storage capacity of 46.42 million tons. PP 02 and PP 03, located in close proximity, have seven and six oil and gas fields, respectively. These plants have ten oil and gas fields within a 75 km and 200 km radius, with a total storage capacity of 447.20 million tons and 3,369.18 million tons, respectively. PP 05, PP 07, and PP 08 collectively have a large full CO_2 storage capacity of 1,767.24 million tons in 14 oil and gas fields within a radius of 50 km. In addition, this 50 km distance is quite economical for CCS applications[13]. Of the three power plants, PP 05 has 14 nearby oil and gas fields within a 50 km radius, with a CO_2 storage capacity of 1,767.24 million tons. Generally, PP 02, PP 03, PP 04, PP 05, PP 07, and PP 08 have the closest number of potential oil and gas fields at a radius of 50 km and 75 km and large storage capacities as well. While this presents a promising scenario for storing emitted CO_2 from power plants, a thorough evaluation of the potential for CCS retrofit is necessary, considering technical, cost-effective, and realistic aspects[7].

The total CO_2e emissions generated from the eight power plants under investigation was 3,228,801 tons/year. It can be retrofitted with oil fields within various radius including 50 km, 75 km, and 200 km with a storage capacity of 1,790.53 million tons, 2,962 million tons, and 3,409.94 million tons, respectively.

Table 6. Number of oil and gas fields closest to CO2 storage on eight power plants within a radius of 50 km, 75 km, and 200 km

Power Plants	Emission CO2e (ton/year)	Radius of 50 km		Radius of 75 km		Radius of 200 km	
		Number of fields	Total storage capacity (million tons)	Number of fields	Total storage capacity (million tons)	Number of fields	Total storage capacity (million tons)
PP 01	102,180	-	-	-	-	4	46.42
PP 02	1,221,319	7	27.09	10	447.20	37	3,369.18
PP 03	252,220	6	23.29	10	447.20	37	3,369.18
PP 04	211,199	2	2.67	13	1,412.04	35	3,364.62
PP 05	152,064	14	1,767.24	19	2,944,01	35	3,364.62
PP 06	186,394	-	-	-	-	4	46.42
PP 07	1,043,206	12	1,408.24	17	2,805,64	35	3,364.62
PP 08	60,219	12	1,408.24	17	2,805.64	35	3,364.62

3.4 Power plant selection

Although this selection provides an aggregate representation of the theoretical potential for CCS retrofits, it offers readers an insight into the hierarchy of opportunities and the possibility of CO_2 source-sink dynamics in the East Kalimantan region. Figure 5 shows the power generation capacity and age status of the eight CFPPs in East Kalimantan.

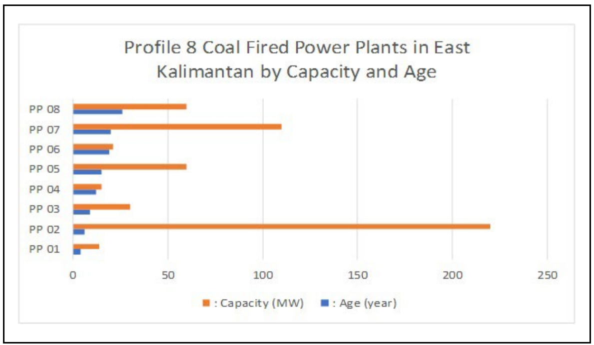


Fig. 5: Status of 8 Coal Fired Power Plants in East Kalimantan by Electricity Capacity and Age

There is only one power plant, PP 01, below the age of five, with an electricity capacity of 14 MW. However, it is not recommended to apply CCS retrofitting due to its low electricity capacity, making it potentially uneconomical[13,14]. Power plants below the age of ten, namely PP 01, PP 02, and PP 03, possess an electricity capacity of 14 MW, 220 MW, and 30 MW, respectively. PP 01 and PP 03 are not recommended for applying CCS retrofit due to its relatively low electricity capacity. Therefore, only PP 02 can be recommended for CCS retrofit due to its relatively young age of six years and its sufficiently large electrical capacity of 220 MW. PP 04 and PP 05 were categorized as power plants less than 15 years old, with 15 MW and 60 MW electricity capacities, respectively. Based on the same reasons and assumptions, these two power plants are also not recommended for the application of CCS retrofits. Furthermore, similar evaluations were performed for those below 20 years of age and older. Two existing power plant units, PP 07 and PP 08, despite having a considerable generation capacity of 110 MW, were considered too old for CCS retrofit and were consequently excluded from the research. Therefore, of the seven power plants under 20 years, PP 01, PP 03, PP 04, PP 05, and PP 06 were not recommended for CCS retrofit due to the low electricity capacities of 14 MW, 220 MW, 30 MW, 15 MW, 60 MW, 21 MW, and 100 MW, respectively. PP 07 and PP 08, despite having sufficient capacity, were excluded due to its advanced age of 20 years and older, as these plants need to meet the criteria for applying CCS retrofit based on unfavorable lifespan dimensions.

Following the technical potential assessment, considering power plants under the age of ten years and possessing an electricity generation capacity exceeding 200 MW, PP 02 unit was selected as the main candidate for CCS retrofit. With a mere six years of age and a substantial power generation capacity of 220 MW, it is an ideal source to implement carbon capture and storage measures to reduce GHG emissions. However, further research needs to be conducted, taking into account specific factors such as location feasibility, availability of space for retrofit devices, proximity to oil and gas fields, suitable CO_2 storage aquifers, cost-effective transportation, technical possibility of retrofit, existing infrastructure access, economic attractiveness, legislative support, and societal acceptance.

3.5 Special case: Retrofitting power plant 02

The data on the nearest oil and gas field from the PP 02 power plant within a radius of 50 km, along with its CO_2 storage capacities, are shown in table 7. The PP 02 unit, emitting 1,221,319 tons/year, is surrounded by seven depleted oil and gas fields within a 50 km radius, with a total storage capacity of 27.09 million tons. This capacity enables the continuous storage of CO_2 emissions from PP 02 for 22 years. Expanding the radius to 75 km, the PP 02 unit was surrounded by ten depleted oil and gas fields with a storage capacity of 447.20 million tons, allowing for the continued storage of CO_2 emissions from the power plant for approximately 366 years. Within a 200 km radius are 37 depleted oil and gas fields with a storage capacity of 3,894.54 million tons, implying excess CO_2 storage capacity in the area. Therefore, the prospect of CCS retrofit in the PP 02 power plant is promising and can be implemented using a clustering radius of 50 km and 75 km.

Table 7. Oil and gas fields are within 50 km and 75 km radial distance from the PP 02 power plant.

Oil and gas field	Distance (km)	Storage capacity (million tons)	
		50 Km	75 Km
OF16	18.01	0.17	0.17
OGF14	20.80	4.15	4.15
OF12	27.78	0.58	0.58
OF03	29.82	5.29	5.29
OGF08	32.92	12.8	12.8
OF15	33.82	0.30	0.30
OF04	49.81	3.80	3.80
OGF01	65.47		355.20
OGF06	65.51		60.68
OGF22	67.54		4.23
Total		**27.09**	**447.20**

A conceptual program was developed for the CO_2 injection pipeline network linking the PP 02 power plant to the nearest onshore oil and gas fields. This initiative starts at the closest field and extends to others, collectively providing a total storage capacity exceeding 3 million tons per year. Furthermore, the program allows for potential extensions to the next nearest oil and gas field based on suitability and feasibility, particularly when the lifetime of the PP 02 power plant is extended through upgrading and modernization. Table 8 shows the sequence of sink target from the PP 02 power plant to the nearest oil and gas fields. Meanwhile, the map of the probable conceptual pipeline connecting the PP 02 power plant to the sequence of the nearest oil and gas fields designated as CO2 injection targets is shown in **Fig**. 6.

Table 8. The sequence of sink target from PP 02 power plant to the nearest oil and gas fields

Oil and gas field/sink	Storage capacity	Oil and gas field/sink
OF-03	5.29	4.34
OF-04	3.80	3.11
OGF-22	4.23	3.47
OF-01	28.49	23.35
OF-05	3.03	2.48
OF-07	2.95	2.42
Total	**47.79**	**39.17**

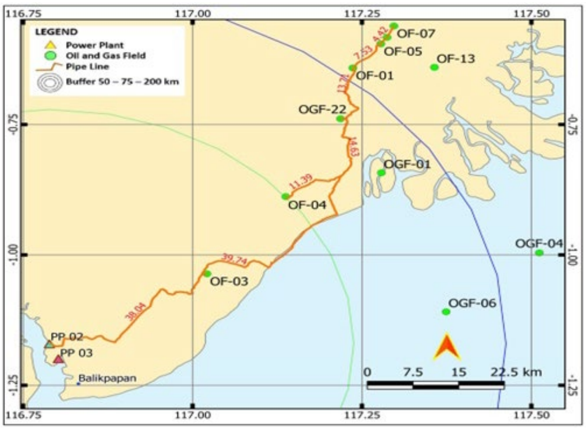


Fig.6: Conceptual pipeline network for target sink from PP 02 power plant to the nearest oil and gas fields (onshore)

The estimated CO2 storage capacity in East Kalimantan, including the source-sink matching process between eight CFPP units as carbon dioxide sources and the nearest oil and gas fields as sinks, shows the high potential for CCS in the region. This assessment is in line with the Government of Indonesia NZE target. Among the eight CFPPs analyzed, collectively emitting 3,228,801 tons/year of CO_2e, retrofitting is feasible within a 50 km, 75 km, and 200 km radius, with a storage capacity of 1,790.53 million tons, 2,962 million tons, and 3,409.94 million tons, respectively. The PP 02 power plant has the potential to carry out CCS retrofitting based on its relatively young age (six years from commissioning), 220 MW electricity generation capacity, and it emits 1,221,319 tons/year of GHG. It is surrounded by seven depleted oil and gas fields within a 50 km radius, offering a storage capacity of 27.09 million tons, capable of continuously storing CO_2e emissions for 22 years. In contrast, for areas within a radius of 75 km, PP 02 was facilitated by ten depleted oil and gas fields with a storage capacity of 447.20 million tons. Lastly, in the 200 km radius, there are 37 depleted oil and gas fields with a storage capacity of 3,369.18 million tons. The conceptual pipeline network for the sink target, linking PP 02 to the nearest onshore oil and gas fields, has also been illustrated. The overall prospect of implementing CCS at PP 02 appears feasible, using either a 50 km or 75 km clustering radius. This positions PP 02 as a suitable candidate for a retrofit pilot with oil and gas fields to reduce the CO_2 emissions produced effectively. But more research is required, considering particular factors like location viability, space availability for retrofit devices, closeness to oil and gas fields, appropriate CO2 storage aquifers, affordable transportation, retrofit technical viability, access to existing infrastructure, economic attractiveness, legislative support, and societal acceptance.

However, in order to meet the NZE target, energy transition initiatives are still being carried out using renewable energy, and utilizing eco friendly [32,33]. Since the energy transition is a lengthy process that needs to be completed by countries in the world, currently dependence on fossil energy, especially coal, is still high. Efforts to reduce emissions at CFPPs is possible to use co-firing with biomass, using coal fly ash [34,35], and CCS/CCUS technology.

Indonesia is introducing a carbon tax using the Cap and Tax scheme, a hybrid model integrating carbon tax and trading. Under this system, companies exceeding the allowable carbon emissions limit are required to pay for the surplus. This payment method has two options, namely carbon emissions trading or tax[36]. As the country migrates towards a cleaner carbon economy, decarbonization and NZE by 2060, power plants need to ensure significant decrease in CO_2 emissions. This study is a preliminary investigation of a beneficial operational scheme for companies operating under a carbon emission economy.

The recent trend in carbon sequestration has also led to the use of captured CO_2 for CO_2-based enhanced oil recovery (CO_2-EOR). Recent research has reported that CO_2-EOR is the most effective method among related schemes in the petroleum industry[37]. This is in line with the vision of achieving net zero emission/NZE with various research focusing on the importance of CO_2-EOR in this context[38]. In a broader perspective, several investigations have explored the connection between carbon sources and sinks, particularly in depleted reservoirs[39]. Captured combustion gas with low CO_2 content and rich in other gases such as carbon monoxide or flue gas, can also be used as an EOR agent[40]. Given these potentials, the source – sink matching carried out for CCS application in East Kalimantan can be used as captured combustion gasses in CCUS schemes. Similarly, major oil fields in the region such as Attaka, Handil, and Bekapai benefit from improved oil production through CO2-EOR. This process, contributes to a brighter prospect of CCUS-ready power plants in East Kalimantan.

4. Conclusion

In conclusion, the assessment of CO2 storage capacities for the 47 suitable oil and gas fields in the East Kalimantan region resulted in a storage capacity ranging between 3,584 and 3,793 million tons for the two cases adopted. A total CO_2e emission of 3,228,801 tons/year was roughly generated from the eight power plants in the region. These emissions could potentially be retrofitted using oil and gas fields within a radius of 50 km, 75 km, and 200 km from the power plants, with storage capacities of 2,088.96 million tons, 3,417 million tons, and 3,971 million tons, respectively. Conceptually, storing emitted CO_2e appeared feasible with such a large storage capacity. However, for a successful CCS application, it was necessary to evaluate the potential for a retrofit by considering its technical, cost-effective, and realistic potentials.

The largest power plant in the East Kalimantan region, codenamed PP 02, was considered to have the potential for CCS retrofitting due to its relatively young age (six years) and sufficiently large electricity generation capacity of 220 MW. It emitted 1,221,319 tons/year of greenhouse gas (GHG) and was surrounded by seven depleted oil and gas fields within a radius of 50 km, offering a storage capacity of 27.09 million tons capable of accommodating CO_2 emissions for 22 years. For practical application, further research needs to be conducted, taking into account specific factors such as availability of space for retrofit equipment, location of oil and gas fields, CO_2 storage aquifers with favorable distance and cost-effective transportation, technical possibilities for retrofit, access to infrastructure, economic attractiveness, adequate legislative support, and social acceptance.

Many oil and gas fields in the East Kalimantan region have sufficiently large CO_2 storage capacities. With the initiation of the carbon economy in Indonesia, any plans to establish a new power plant in this region must be equipped with a CCS retrofit. This was facilitated by the availability of numerous depleted oil and gas fields serving as ready sinks. Spatial analysis and mapping locations close to the storage areas were essential to maintain the coal-fired power plant activities in line with the national net zero emission (NZE) target. This study served as a preliminary investigation, offering a macro-overview of CO_2e source-sink condition in the East Kalimantan region.

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Nomenclature

NZE	Net Zero Emission
CFPP	Coal-Fired Power Plants
GHG	Green House Gasses
CCS	Carbon Capture Storage
CCUS	Carbon Capture Utilization and Storage
EOR	Enhanced Oil Recovery
IEAGHG	International Energy Agency Greenhouse Gas
IPCC	International Panel on Climate Change
EPRI	Electric Power Research Institute
NETL	National Energy Technology Laboratory
WEPP	World Electric Power Plant
HHV	Higher Heating Value
LHV	Lower Heating Value
OOIP	Original Oil in Place
OGIP	Original Gas in Place
URR	Ultimate Recovery Factor
RF	Recovery Factor
FVF	Formation Volume Factor
Bo	Formation Volume Factor Oil
Bg	Formation Volume Factor of Gas
OGF	Oil and Gas Field
OF	Oil Field
GF	Gas Field
PP	Power Plant
GIS	Geography Information System
EPSG	European Petroleum Survey Group
WGS	World Geodesion System

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