Conceptual Models of Hybrid CO_2-EOR Storage in East Kalimantan Based on Source-Sink Matching for Improving Oil Recovery and Pursuing Net Zero Emission

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Abstract: The transition to renewable energy is crucial to achieving decarbonization objectives. The successful deployment of Carbon Capture and Storage (CCS) and Carbon Capture, Utilization, and Storage (CCUS) technologies will be of utmost importance to achieve Net Zero Emissions. Hybrid CO_2-EOR will present a more attractive alternative since the economic benefits of increased oil production offset the costs of CCS. This study proposes conceptual models of hybrid CO_2-EOR and storage in East Kalimantan, Indonesia. Source-sink matching was performed from the emission source to oil field buffers within 50 km and 100 km. The results show that in East Kalimantan, CO_2 emissions reached 9.5 gigatons (Gt) CO_2e/year, whereas the total storage capacity of depleted oil fields is approximately 3.43 Gt CO_2e/year. Hybrid storage and CO_2-EOR can increase oil recovery by 1.29 billion barrels, with a total recoverable reserve of 5.36 billion barrels. According to source-sink matching and clustering, all emissions could sink to the surrounding depleted oil fields. This research implies that the prospect of CO_2-EOR and hybrid storage in the East Kalimantan region is profoundly attractive. In addition, the findings provide valuable guidelines for policymakers in designing region-specific carbon management strategies that support economic incentives with emission reduction goals.

Keywords: CCS-CCUS; CO2 emissions; depleted oil and gas fields; energy modeling; petroleum industry; sedimentary basin

1. Introduction

Indonesia aims to reach a Net Zero Emission (NZE) target by 2060[1)]. However, the business-as-usual scenario shows that until 2060, more than 75% of energy needs will come from fossil fuels[2)]. The use of fossil fuels as an energy source causes significant air pollution which makes it an international concern[3)]. The dominance of CO_2 emissions in Indonesia comes from the use of coal-fired power plants, followed by the transportation sector[4)]. The transition to renewable energy is of considerable importance in achieving this decarbonization. Therefore, Carbon Capture and Storage (CCS) and Carbon Capture Storage and Utilization (CCUS) must be prepared to fulfill the NZE target. This method is essential to accommodate the massive emission reduction in depleted oil and gas fields and aquifers[5)]. CCUS is one of the advanced technologies that can significantly reduce the environmental impact of global warming and climate change[6)]. Through establishing a new "atmosphere-to-atmosphere" carbon cycle, CCUS technology is instrumental in reaching carbon neutrality[7)] as an indispensable tool for decarbonization[8)]. CCUS reduce enormous CO_2 emissions from various industries, making it a valuable technology for climate change mitigation[9)]. Moreover, it provides the opportunity to assist a country/region in reaching global carbon goals[10)], contributes to emission reduction, decreases raw material consumption[11)], and promotes the transition process to a circular economy[12)]. A previous study in East Kalimantan reveals that coal-fired power stations can be retrofitted with CCS to satisfy the net-zero

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emission objective[13].

CO_2 emissions from fossil-based power plants will remain high without intervention[2]. The previous study from Sabtu *et al.* highlights the importance of integrating carbon management into supply chain planning[14], which supports the need for efficient CO_2 logistics and utilization systems in hybrid CO_2-EOR storage projects in East Kalimantan. Therefore, mitigation strategies are needed such as CO_2 capture and utilization through hybrid CO_2-EOR technology. The utilization of CO_2 for increased oil recovery (CO_2-EOR) offers a more commercial opportunity as the economic benefits from additional oil production will balance CCS costs[15]. In the injection phase of EOR, a substantial amount of the injected CO_2 was trapped in the reservoirs[16]. However, large-scale storage of pure CO_2 in depleted fields and closure of a large-scale CO_2-EOR site should be tested[17]. Another study suggests specific screening parameters for depleted fields such as depth, capacity, injectivity, number of legacy wells, infrastructure, pipeline, production history, available 3D seismic and well logs, regulatory readiness, and local community acceptance[18].

The integration or hybrid method of CO_2-EOR and storage proves advantageous, particularly due to the increased oil production as revenue[19]. This integration was performed in the Anadarko basin with a target of sequestering one million metric tons of CO_2 within an active EOR project[20]. China has shown success in chemical injection applications[21], while several injections and studies have been carried out for the CO_2 industry[22]. A study of China's onshore showed the potential to increase oil production by 7.7 billion barrels and store 2.2 billion tons of CO_2 from 296 oil fields[23]. A total of 49 CCUS pilots and fields tests are under construction in China, while about 169 trials were completed in 2021[24]. Sinopec showcased a significant CCS project of flue gas FCC (fluid catalytic cracking), which integrated CCS and EOR components[25]. Numerous integrated projects are in various stages of study[26], including full-scale investigations[27], trials, pilots, field tests[28], and injection assessments[29]. In Indonesia, CCUS studies have been conducted on the depleted oil and gas in South Sumatra. The results of EOR screening indicated that 18 fields were immiscible, 77 fields miscible, and 7 fields failed, whereas the total incremental oil recovery estimate was 480.5 MSTB, and the total CO_2 storage estimate was 92 million tons[30]. Source and sink matching has been carried out for South Sumatra, West Java, and East Java areas, with most of the fields concentrated in a total of 176 CO_2 sources estimated, and their emission amounts to about 170 $MtCO_2$/year[31]. The top three ranked basins from screening studies are Kutai, Tarakan, and South Sumatra[32] based on factors such as relatively stable geological structure and established infrastructure[33]. Kalimantan is a strategic region in the future energy system because it is directly connected to the main energy regions (Java, Madura, Bali, Sumatra) in the NZE scenario[34]. The oil and gas fields in Kalimantan are in the eastern part of the Barito, Tarakan, Kutai, and Pasir basin, as well as in the Sarawak basin off the northwest coast[35]. Oil and gas fields are trapped within the delta system in East Kalimantan[36]. The Kutai basin is a significant oil and gas producer, formed by the Mahakam Delta complex. Within this basin, there are formations of Kiham Haloq, Balikpapan, and Kampung Baru, with Balikpapan, and Kampung Baru as the most productive, as characterized by litharenite and lithic sand surface porosity reservoirs ranging from <5% – 25% with permeability <10 mD – 200 mD[37].

East Kalimantan has refineries, factories, oil and gas gathering stations producing gas emissions. Moreover, mature oil and gas fields usable as storage for emission are also available. Strong prospects for CCS/CCUS in East Kalimantan are created by the increased upstream and downstream oil activities, the demand for new refineries, and the energy transition movement[38]. The proximity of CO_2 emission sources such as oil refineries, power plants, and oil and gas fields support the implementation of CCUS-EOR programs as a strategy to increase oil production while reducing emissions[39]. Mining, together with oil and gas industries in East Kalimantan, has had wide impacts on the economy, society, and environment and at the same time has left many unused industrial sites (brownfields) that could be utilized for CO_2 storage or adapted for CO_2-EOR projects[40]. Thus, this study aimed to examine the prospect and to propose the conceptual model of hybrid CO_2-EOR and storage in East Kalimantan, Indonesia, for improving oil recovery, mitigating CO_2 emissions, and achieving NZE.

Source-sink matching in the context of CCUS refers to the strategic process of linking CO_2 emission sources with appropriate storage or utilization sites (sinks)[41] as described in Figure 1. A conceptual pipeline network is subsequently designed to transport captured CO_2 from sources to sinks, involving a complex system of pipelines, compression stations, and, where necessary, intermediate storage facilities.

2. Methodology

2.1. Study Area

Kutai basin as the study location is a basin located onshore and offshore on Borneo Island, Indonesia (Figure 2). Borneo Island has 13 sedimentary basins with the status of 4 production basins, 2 basins with hydrocarbon discoveries, 4 basins with geological and geophysical data, and 3 frontier basins. According to Sedimentary Basin Map of Indonesia from Ministry of Energy and Mineral Resources,

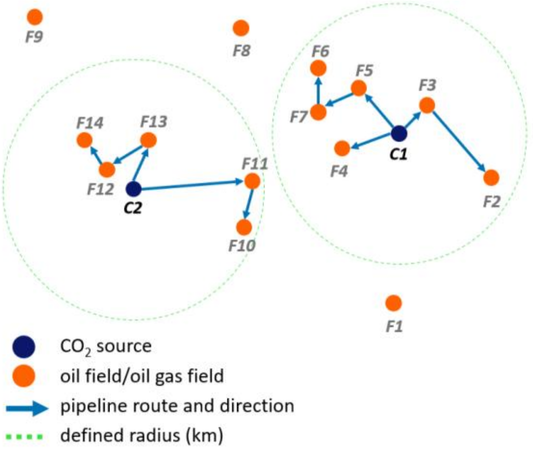

Fig. 1: Conceptual diagram of source-sink matching and the pipeline

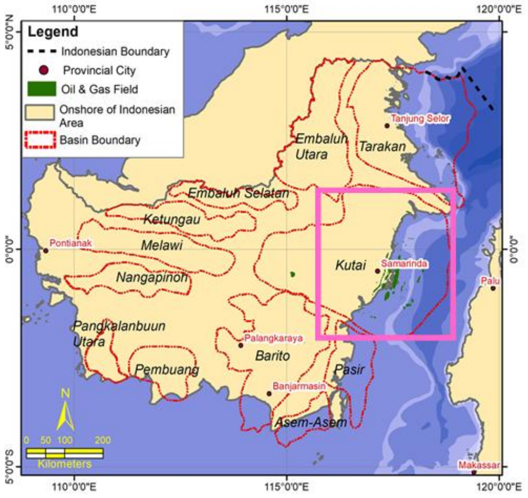

Fig. 2: Study area and Basin location in Borneo Island

Republic of Indonesia, Kutai basin area covers a total of 130,970 square kilometers. Kutai Basin is the best basin for CO2 storage on Borneo Island in terms of size, basin depth, sediment thickness and reservoir depth[33)]. In the basin there are 8 coal fired power plants close to oil and gas fields with a total CO2 emissions of around 3.2 million CO2e tons/year[13)]. In general, the use of fossil energy such as oil, natural gas and coal in Borneo is still the main source that covers 80% of energy requirements indicating the need for immediate and serious intervention of high CO2 emissions[40)].

2.2. Data collection

CO_2 emission sources, quantity emitted, as well as depleted oil and gas fields in East Kalimantan were used as data resources. Collaboration with environmental agencies was conducted to compile data, along with secondary data that had been previously published. The required data sets from refineries included locations, land area, train, refinery layout, production capacity, CO_2 emission, and other supporting data. Balikpapan and Bontang oil refineries stand out as the two largest in East Kalimantan. Emission data in East Kalimantan were collected from refineries, fertilizer and chemical plants, as well as oil and gas gathering stations. In this study, the focus was principally on the quantity of CO_2 emission sources. Data for depleted oil fields were obtained from the Directorate General of Oil and Gas, Ministry of Energy and Mineral Resources, Indonesia.

2.3. Production forecast and EOR potential analysis

The calculation of the estimated CO_2 storage capacity is carried out using the production prediction method with decline curve. Specifically, data from 22 oil fields in saturated and 17 in undersaturated reservoirs were used to analyze CCUS/CO_2-EOR conditions. The oil and gas fields are located onshore and offshore East Kalimantan This is used as a reference for the NZE achievement plan initiated by the Indonesian government.

The estimation of CO_2 storage capacity in an oil reservoir is made based on the concept of voidage replacement, which CO_2 injected equates to the volume of fluid withdrawn from the reservoir. This concept assumes that production or injection of water is non-existent. The calculation for CO_2 storage capacity in oil fields and gas field follows Bachu's formula that is based on original oil in place (OOIP) and original gas in place (OGIP)[42)]. The formula used to calculate the CO_2 storage capacity (CSC) can be seen in Equation 1 and Equation 2 below,

$$CSC_{oil\,reservoir} = OOIP \times RF \times B_o \times CO_2\,density \qquad (1)$$

$$CSC_{gas\,reservoir} = OOIP \times RF \times B_g \times CO_2\,density \qquad (2)$$

where, CSC = CO_2 storage capacity in million metric tons (Mt), OOIP = original oil in place in thousands of Stock Tank Barrels (MSTB), OGIP = original gas in place in cubic meters (m^3), RF = recovery factor, B_o and B_g are formation volume factors for oil and gas, respectively. Whereas B_o unit in RB/STB, and the B_g unit in cu-ft/SCF.

2.4. CO_2-EOR scenarios for enhanced oil production

With assumes the absence of reservoir properties data for CO_2-EOR screening, the increase in oil production due to CO_2 injection was assumed by using two methods. Therefore, two scenarios for calculating storage capacity and ultimate oil recovery were: (1) baseline scenario, assuming that recoverable recovery (RR) is similar to the ultimate recoverable reserve (URR) at primary recovery, and that CO_2 storage capacity is calculated based on URR; (2) optimistic scenario, assumes that ultimate oil recovery is equal to URR[43)] plus an additional 12% of OOIP[44)] and CO_2 storage capacity that is calculated accordingly, Assuming in this second model there is a miscibility of the CO_2 injected into the reservoir.

2.5. Source-sink matching and conceptual pipeline

The arrangement of emission sources and oil fields for CO_2-EOR injection and storage were carried out using QGIS ver. 3.16, with coordinate reference system ESPG (European Petroleum Survey Group) 4235 – WGS (World Geodetic System) 84. Source sink matching was performed from one CO_2 emission source to several oil field buffers within a radius of 50 km and 75 km[31)], then the conceptual pipeline network from the source to the nearest onshore oil fields was constructed. This is usually done by following existing infrastructure, such as roads and other public facilities.

3. Results and discussions

3.1. Oil production forecast and EOR potency in East Kalimantan

The forecast of total oil production from 39 fields indicated a sharp decline, whereas oil reserves of East Kalimantan showed that the ultimate recovery was approximately 4.3 million barrels of oil; the remaining reserves in the same year amounted to only 0.37 million barrels (Figure 3 above). Thus, to increase oil recovery, EOR technology, including CO2 injections, needs to be implemented. The production improvement of CO2-EOR ranged from 6 to 12% OOIP. This method is expected to increase oil production by up to 60% (Figure 3 below).

3.2. CO_2 emission sources and storage availability

Despite the fact that significant emissions from oil and gas processing and factories that use fossil fuels are still recorded in East Kalimantan, the region has many oil-depleted fields. To leverage this, hybrid CO2 storage and EOR pilots were carried out to achieve NZE. CO2 emissions in East Kalimantan emanate from 2 refineries (RF), 4 fertilizer and chemical plants (FAC), as well as 9 oil and gas gathering stations (GS), whereas the storage availability comes from 22 oil gas fields and 17 oil fields (Figure 4).

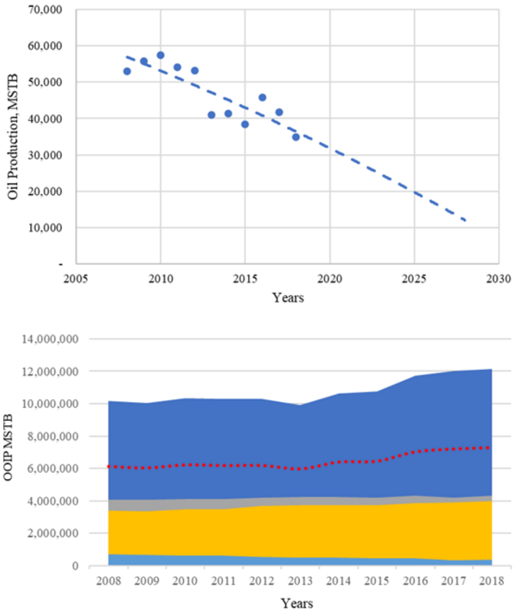

Fig. 3: Total oil production forecast (above) and EOR potency (below) in East Kalimantan

The total CO_2 emissions per year reach more than 9.5 gigatons (Gt) CO_2e tons. The highest contribution of CO_2 emissions mainly arises from refineries about 4.1 Gt CO_2e/year, followed by fertilizer chemical plants and oil & gas gathering stations with 3.5 and 1.89 Gt CO_2e/year, respectively (Table 1).

Given that this study focused on emissions totaling approximately 1 million CO_2e (tons/years), RF1, RF2, FAC1, FAC2, and GS9 were retrofitted for CCUS or CCS. These retrofits aimed to facilitate the integration of depleted oil fields for both CO_2 storage and improving oil recovery, thereby contributing to a reduction in CO_2 emissions. Regarding storage availability in depleted oil fields, the RR is estimated at an additional 6% of OOIP using a pessimistic criterion and 12% in an optimistic scenario.

Based on the increase in oil production at the primary and tertiary stages, as well as CO_2 storage capacity from oil and gas fields (Table 2), the total storage capacity across 22 fields is approximately 429.13 Mt in oil zone, and 2,917 Mt in the gas zone, with a total of 3.35 Gt CO_2e. In addition, the improvement in oil recovery amounts to 1.036 billion barrels, with a total oil of 4.377 million barrels. Table 3 shows CO_2 storage and improvement in oil recovery across the 17 oil fields. The total storage capacity is approximately 84 million tons of CO_2e at an optimistic EOR. The improvement in oil recovery reaches 250 million barrels, and the total is 981.9 million barrels. The total storage capacity of depleted oil fields is approximately 3.43 Gt, therefore, when storage capacity is divided by emission per year, it results in approximately 360 years.

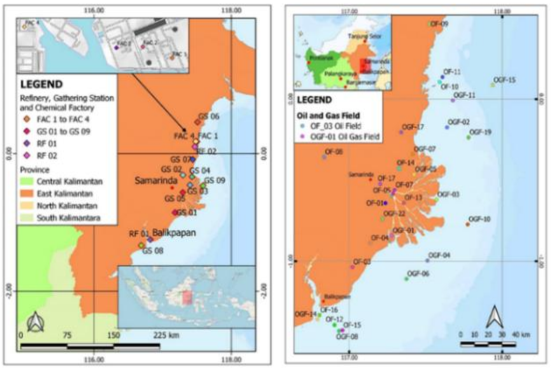

Fig. 4: Location of CO_2 emission sources (left) and oil and gas fields (right) in East Kalimantan

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Table 1: The amount of CO_2 emissions in East Kalimantan

Emission Sources	Code	Operation Year	Production	Emission Year	CO_2 Emission (CO_2e tons/year)
Refineries	RF1	1980	360 MBSD (fuel oil)	2022	1,565,260.63
	RF 2	2008	22.5 Mt/yr (LNG)	2022	2,575,692.63
Fertilizer Plant and Chemical Plant	FAC1	1977	5,166,150 T/yr (urea fertilizer)	2022	2,250,945.24
	FAC2	2003	1500 MTPD (ammonia)	2021	983,138.00
	FAC3	1999	2000 tons (methanol)	2022	106,406.64
	FAC4	2012	300,000 T/yr (ammonium nitrate)	2022	163,526.99
Oil & Gas Gathering Station	GS1	2018	27,000 BOPD and 155 MMSCFD (oil and gas)	2021	83,594.35
	GS2	2018	35,000 BOPD and 200 MMCFD (oil and gas)	2021	69,469.25
	GS3	2018	40,000 BOPD and 700 MMSCFD (oil and gas)	2021	54,664.74
	GS4	2018	15,000 BOPD and 650 MMSCFD (oil and gas)	2021	62,445.56
	GS5	2005	246,672 BOPD (oil)	2022	18,668.74
	GS6	2005	10,000 BOPD (oil)	2021	17,819.88
	GS7	1973	204,000 BOPD and 300 MMSCFD (oil and gas)	2021	198,210.09
	GS8	1973	50,000 BOPD and 100 MMSCFD (oil and gas)	2021	147,550.19
	GS9	2018	230,000 BOPD and 3000 MMSCFD (oil and gas)	2021	1,231,958.00
				Total	**9,529,350.93**

Notes: MBSD= thousand barrels per stream day; MT/yr. = million tons per year; LNG= liquid natural gas; MTPD= metric tons per day; T/yr = ton per year; BOPD = barrel oil per day; MMSCFD= million standard cubic feet per day

Table 2: Storage and improvement in oil recovery at oil and gas fields

Field Code	Oil Zone				Gas Zone		Oil Recovery CO_2-EOR
	Baseline Scenario		Optimistic Scenario		URR (BSCF)	Storage CO_2 (Mt)	
	URR (MSTB)	Storage CO_2 (Mt)	URR (MSTB)	Storage CO_2 (Mt)			
OGF-01	973,804	102.62	1,172,044	123.51	3,440	252.58	198,240
OGF-02	691,370	66.00	970,028	92.60	2,588	251.82	278,658
OGF-03	293,441	32.97	410,817	46.15	9,610	682.32	117,376
OGF-04	234,289	27.87	282,769	33.63	678	49.82	48,480
OGF-05	106,008	16.30	123,489	18.99	4,396	268.50	17,481
OGF-06	119,228	14.81	166,919	20.73	4,756	45.88	47,691
OGF-07	115,072	12.51	138,725	15.08	6,470	802.45	23,653
OGF-08	149,628	9.69	192,204	12.45	616	3.12	42,576
OGF-09	54,030	8.08	58,350	8.72	1,105	177.42	4,320
OGF-10	52,064	7.33	54,779	7.71	1,249	114.03	2,715
OGF-11	77,949	4.76	91,970	5.62	642	45.68	14,020
OGF-12	48,329	4.61	69,054	6.59	56	5.44	20,725
OGF-13	118,596	4.42	213,633	7.96	344	16.30	95,036
OGF-14	62,853	4.07	77,666	5.03	17	0.08	14,812
OGF-15	40,432	3.86	59,841	5.71	322	31.30	19,409
OGF-16	22,400	3.15	25,112	3.53	516	47.11	2,712
OGF-17	69,208	3.13	96,250	4.35	778	77.18	27,042
OGF-18	55,584	2.28	77,823	3.19	86	12.00	22,240
OGF-19	16,994	1.62	34,312	3.28	162	28.58	17,318
OGF-20	13,943	1.47	19,801	2.09	16	1.20	5,858
OGF-21	6,601	0.70	12,957	1.37	16	1.19	6,356
OGF-22	19,118	0.56	28,467	0.84	178	3.66	9,348
Total	**3,340,943**	**332.81**	**4,377,011**	**429.13**	**38,041**	**2,917.66**	**1,036,068**

Notes: URR= ultimate recoverable reserve; MSTB= thousand stock tank barrels; Mt= million metric tons; BSCF= billion standard cubic feet

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Table 3: Storage and improvement in oil recovery at oil fields

Field Code	**Oil Zone**				**Oil Recovery CO_2-EOR**
	Baseline Scenario		**Optimistic Scenario**		
	URR (MSTB)	**Storage CO_2 (Mt)**	**URR (MSTB)**	**Storage CO_2 (Mt)**	
OF-01	185,250.41	28.49	235,678.01	36.24	50,427.60
OF-02	202,110.20	7.53	259,316.84	9.67	emanate 57,206.64
OF-03	69,659.87	5.29	88,422.71	6.71	18,762.84
OF-04	50,053.43	3.80	73,836.00	5.60	23,782.57
OF-05	35,982.75	3.42	48,162.03	4.57	12,179.28
OF-06	35,363.59	3.38	46,280.99	4.42	10,917.40
OF-07	31,077.50	2.95	41,706.50	3.96	10,629.00
OF-08	16,776.58	2.58	20,407.42	3.14	3,630.84
OF-09	47,095.92	2.12	85,429.56	3.85	38,333.64
OF-10	19,439.87	1.19	28,872.47	1.76	9,432.60
OF-11	14,081.16	0.86	18,103.08	1.11	4,021.92
OF-12	9,001.30	0.58	12,790.66	0.83	3,789.36
OF-13	5,441.94	0.52	7,486.50	0.71	2,044.56
OF-14	2,594.53	0.40	3,277.56	0.50	683.03
OF-15	4,672.07	0.30	6,563.99	0.43	1,891.92
OF-16	2,559.78	0.17	3,659.34	0.24	1,099.56
OF-17	609.13	0.09	1,949.53	0.30	1,340.40
Total	**731,770.03**	**63.67**	**981,943.19**	**84.04**	**250,173.16**

Notes: URR = ultimate recoverable reserve; MSTB = thousand stock tank barrels; Mt = million metric tons

Comparison between the ultimate recovery and the remaining reserves underscores the need for CO_2-EOR implementation due to the substantial amount of oil trapped in the reservoirs. Storage capacity was calculated using the voidage replacement method, which considered the fluid produced at the optimal level (URR) during the primary recovery stage, and the additional RR at CO_2 injection EOR stage. The results of total storage capacity and the improvement in oil recovery indicated that the application of hybrid CO_2 storage and EOR is not only allowed for the sequestration of CO_2 emissions into the ground but also has improved oil recovery.

3.3. Conceptual models of source and sink hybrid

All the locations of oil fields were close to the emission sources within 50 km and up to 200 km. Given this proximity, a distance below 50 km was selected for the initial stage, and after a successful pilot, the injection program was relocated to a higher distance. This preliminary phase allowed the testing of CO2 injection into geological formations before broader emission reduction efforts. Modeling and clustering were constructed based on emission with the approximation of one million tons per year. Therefore, CO2 sources from oil refineries of RF1 and RF2, the fertilizer plant of FAC1, as well as oil and gas gathering stations of GS09 were selected for buffer zones and source-sink matching (Figure 5).

Two conceptual models of hybrid CO_2-EOR and storage were developed from RF1 and RF2 (Table 4). RF1 to OF3, OF4, and OGF3 fields showed the potential to increase total oil production by about 0.16 billion barrels and store 0.818 Gt CO_2e with an injection time of approximately 523 years, whereas RF2 to OGF17, OGF7, OGF5, and OF14, can increase total oil production by 0.36 billion barrels and store 1.188 Gt CO_2e with an injection time of 461 years.

Based on the distance between the emission source and the oil fields to be injected (Figure 6), CCUS retrofit from RF2 needs to be prioritized. Based on the results of improvement in CO2-EOR and storage across 39 Oil Fields in East Kalimantan, depleted oil fields can effectively sequester emission for an extended period. The hybrid CO2-EOR not only has the potential to improve oil recovery and halt the decline in oil production but also

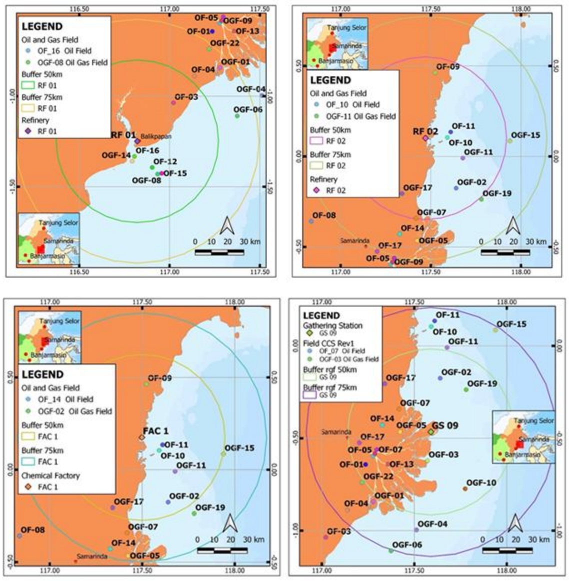

Fig. 5: Oil fields clustering for CO_2 sources from RF1 (upper left), RF2 (upper right), FAC1 (lower left), and GS09 (lower right)

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Table 4: Oil recovery factor and CO_2 storage from refinery sources

CO_2 Source	Fields Code	Improvement Oil Recovery CO_2-EOR (MSTB)	Total CO_2 Storage (Mt)	Injection Time (Years)
RF 1	OF-03	18,762.84	6.71	4.29
	OF-04	23,782.57	5.60	3.58
	OGF-3	117,376.40	805.83	514.82
RF 2	OGF-17	96,250.33	80.92	31.42
	OGF-07	138,725.11	816.25	316.91
	OGF-05	123,488.68	286.14	111.09
	OF-14	683.03	4.70	1.82

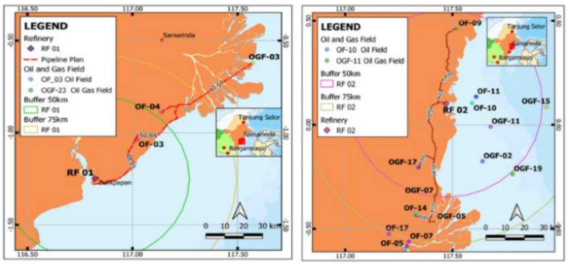

Fig. 6: Conceptual CO_2-EOR and storage pipeline from RF1 (left) and RF2 (right)

store significant amounts of CO2 for a long time in geological formation. This method plays a crucial role in combating climate change by facilitating the process of decarbonization.

In supporting the transition toward net-zero emissions, sustainability in CCUS infrastructure design can be enhanced by incorporating locally sourced or waste-based materials. Waste-derived construction materials, such as rice husk ash and coal bottom ash, have demonstrated a strong potential for sustainable infrastructure development, aligning with the broader goal of reducing lifecycle emissions in CCUS and EOR systems[45)].

3.4. The significance of CO_2-EOR storage for policy development and its implications

CO_2-EOR storage is crucial for Indonesia to maintain its oil and gas production due to the decline in oil production since 2000, which was initially from more than 1 million barrels per day to around 605,000 barrels per day in 2023 then decreased further, reaching 576,000 barrels per day by 2024[46)]. In the last 15 years, the average oil production decline in Indonesia is around 3–4.41% per year[47)]. Therefore, an ambitious project such as CO_2-EOR is required to enhance oil and gas production. The CO_2 injection in the Jatibarang field for 4 days with 250 tons of CO_2 liquid can substantially increase oil and gas production[48)] and estimated that CO_2-EOR storage can increase additional recovery by around 5 - 20% OOIP[49)]. The implementation of CO_2-EOR storage in Indonesia presents two major advantages: it aligns with the national objective of achieving Net Zero Emissions by 2060 and supports the strategic goal of reaching one million barrels per day in oil production by 2030. Specifically on the Borneo Island, CO_2-EOR storage will support the program of the smart, green, beautiful and sustainable city of the new Indonesian capital, as well as the ASEAN CCS hub and network[33)] The viability of this potential is reinforced by the presence of significant CO_2 storage capacity, distributed across mature and depleted oil and gas reservoirs as well as extensive deep saline aquifers, offering a robust foundation for the development of sustainable carbon management strategies.

The design of CO_2-EOR infrastructure can include sustainability considerations at the system level by utilizing green manufacturing concepts, which prioritize resource efficiency and emissions reduction. Furthermore, CO_2 transit logistics, source-sink integration, and long-term storage planning can all be optimized by modifying supply chain optimization techniques employed in advanced manufacturing contexts[50)].

4. Conclusion

This study highlights the conditions in East Kalimantan, a region characterized by intensive oil and gas processing activities and a high concentration of fossil fuel-based industries. The CO_2 storage capacity of depleted oil fields is substantial and can accommodate emissions from stationary sources for an extended period. With a total of 3.43 Gt CO_2e/year capacities, East Kalimantan is estimated to have one of the largest CO_2 storage capacities in Indonesia. There is an excellent opportunity for hybrid CO_2-EOR storage to increase oil production and store CO_2 in depleted oil fields. The viability of CCUS CO_2-EOR is improved by source-sink matching and clustering, which revealed that all emission sources were close to depleted oil fields, particularly those with a volume of one million tons.

The study proposes a spatially integrated CCUS model that connects multiple CO_2 sources to suitable sinks, offering a more realistic alternative to single-source approach and a scalable representation of emission capture potential. A key distinction is its focus on aligning carbon management with future national development. The model supports strategic planning for CO_2 reduction by addressing regional infrastructure potency, making it a practical contribution to Indonesia's emerging CCUS framework.

CRediT authorship contribution statement

Sugihardjo: Conceptualization, Methodology, Writing-Original draft. Devitra Saka Rani: Writing-Reviewing and Editing, Visualization. Bambang Widarsono: Resources, Supervision. Mohamad Romli: Data Collection of subsurface, Data Validation of subsurface. Tri Muji Susantoro: Writing-Reviewing and Editing, Formal analysis of source and sink map. Panca Wahyudi: Data

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Validation of oil and gas fields. Sunting Kepies: Data Collection of subsurface, Formal analysis of subsurface. Nurkamelia: Data Collection of emission, Formal analysis of refineries and industries. Suliantara: Software, Visualization. Diana Dwijanarti: Project administration, Formal analysis of subsurface storage capacity.

Declaration of competing interest

The authors declare that they have no conflict of interest.

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Nomenclature

BOPD	barrel oil per day
CCS	Carbon Capture and Storage
CCUS	Carbon Capture, Utilization, and Storage
CO$_2$	Carbon dioxide
CO$_2$e	CO$_2$ equivalent
cu-ft/SCF	cubic feet per standard cubic foot
EOR	enhanced oil recovery
ESPG	European Petroleum Survey Group
IEA	International Energy Agency
Gt	Gigatons
IEAGHG	IEA Greenhouse Gas R&D Programme
LNG	liquid natural gas
MBSD	thousand barrels per stream day
mD	milli-Darcy
MMSCFD	million standard cubic feet per day
Mt	million metric tons
MSTB	thousand stock tank barrels
MTPD	metric tons per day
NZE	net zero emission
OGIP	original gas in place
OOIP	original oil in place
RB/STB	Reservoir Barrel/Stock Tank Barrel
RR	recoverable recovery
URR	ultimate recoverable reserve
WGS	World Geodetic System

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