A SYSTEMATIC APPROACH TO SOURCE-SINK MATCHING FOR CO_2 EOR AND SEQUESTRATION

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ABSTRAK

Injeksi karbon dioksida untuk peningkatan pengurasan minyak (CO_2 EOR) dapat menaikan produksi minyak secara signifikan dan pada saat yang bersamaan sejumlah CO_2 injeksi tetap tersimpan dalam reservoar sehingga memberi kontribusi terhadap penurunan emisi gas rumah kaca. Keberhasilan CO_2 EOR dengan sekuestrasi tergantung pada integrasi sumber CO_2 dengan reservoar target injeksi. Makalah ini membahas suatu pendekatan sistimatis untuk memasangkan sumber CO_2 yang dihasilkan dari kegiatan industri dengan reservoar-reservoar minyak di cekungan Sumatera Selatan dalam rangka pilot proyek CO_2 EOR. Inventarisasi sumber-sumber CO_2 dan reservoar-reservoar minyak dilakukan melalui survei dan kuesioner. Proses pencocokan sumber-reservoar diawali dengan terlebih dahulu memberi nilai dan peringkat masing-masing sumber dan reservoar menggunakan kriteria yang dikembangkan khusus untuk CO_2 EOR dan sekuestrasi. Peringkat teratas sumber CO_2 dipasangkan dengan beberapa kandidat teratas reservoar target dengan memperhatikan aspek nilai tambah, waktu, injektivitas, kontainmen, dan kedekatan. Dari proses tersebut diperoleh usulan scenario pilot proyek yaitu CO_2 akan diambil dari stasion pengumpul gas, diidentifikasi sebagai GGS, sedangkan lapangan minyak H3 dan F21 sebagai reservoar target. Tujuan pilot proyek adalah memfasilitasi pengembangan CO_2 EOR sekuestrasi ke depan di cekungan Sumatera Selatan yang berdasarkan survei mempunyai potensi CO_2 EOR dengan kapasitas simpan relatif besar dengan sumber CO_2 industri melimpah.

Kata Kunci: pencocokan sumber-reservoar, CO_2 EOR, sekuestrasi CO_2, produksi minyak, sumber CO_2 industri

ABSTRACT

Carbon dioxide for enhanced oil recovery (CO_2 EOR) can magnify oil production substantially while a consistent amount of the CO_2 injected remains sequestrated in the reservoir, which is beneficial for reducing the greenhouse gas (GHG) emission. The success of CO_2 EOR sequestration depends on the proper sources-sinks integration. This paper presents a systematic approach to pairing the CO_2 captured from industrial activities with oil reservoirs in South Sumatra basin for pilot project. Inventories of CO_2 sources and oil reservoirs were done through survey and data questionnaires. The process of sources-sinks matching was preceded by scoring and ranking of sources and sinks using criteria specifically developed for CO_2 EOR and sequestration. The top candidate of CO_2 sources are matched to several best sinks that correspond to added value, timing, injectivity, containment, and proximity. Two possible scenarios emerge for the initial pilot where the CO_2 will be supplied from the gas gathering station (GGS) while the H3 and F21 oil fields as the sinks. The pilot is intended to facilitate further commercial deployment of CO_2 EOR sequestration in the South Sumatera basin that was confirmed has abundant EOR and storage sinks as well as industrial CO_2 sources.

Keywords: *source-sink matching,* CO_2 *EOR,* CO_2 *sequestration, oil production, industrial* CO_2 *sources*

I. INTRODUCTION

The utilization of CO_2 for enhanced oil recovery (EOR) does not only sustain the oil production but also bridges the transition towards low-carbon technology deployment such as carbon sequestration. The CO_2 EOR operations that have been profitable since 1972[10,11], enables providing early technology demonstration of CO_2 injection to the subsurface particularly for Indonesia, increases the public acceptance with respect to the outstanding worldwide safety records of CO_2 injection operations and creates a base platform for CO_2 operation infrastructures. Approximately 40% of the injected CO_2 remains trapped in the reservoirs during the CO_2 EOR operations[9]. Additional recoverycan amount to 5% to 20% of the original oil in place (OOIP) depending on the characteristics of the hydrocarbon and the reservoir conformance[6]. In a future carbon-constrained environment where efforts in reducing GHG is becoming intense, CO_2 EOR in conjunction with CO_2 sequestration will probably become the preferred emission abatement option due to the oil recovered and revenues generated from the CO_2 sales[8].

The success of CO_2 EOR sequestration depends on appropriate pairings of sources and sinks. A good CO_2 source is able to supply constant CO_2 to the sink within certain period while suitable sink has injectivity correspond to the CO_2 supply rate and sufficient storage capacity[4,16]. Source-sink matching process involves analysis of matching the demand and supply of CO_2 in which the characteristics CO_2 produced from the industrial sources are matched to reservoirs properties. Although, natural CO_2 fields are currently the dominant sources for the CO_2 EOR market, industrial sources of CO_2 needed in order to ensure adequate CO_2 supplies to facilitate substantial growth in oil production utilizing CO_2 EOR[1]. For CO_2 EOR sequestration case, the amount of CO_2 required is increased as the sink converted as CO_2 storage. Several factors affecting source-sink matching include CO_2 content, flow-rate, source type, source temperature, source pressure, formation pressure and fracture pressure[3,13]. Source-sink matching provides the identification of potential CO_2 EOR sequestration pilot project and can be designed to find the least-cost pathway[16].

In South Sumatera excellent opportunities exist for CO_2 EOR sequestration application. Within the South Sumatera Basin are mature oil fields with the potential to recover additional oil and store CO_2[18]. Figure 1 indicates that South Sumatra basin is home to the second largest of theoretical EOR

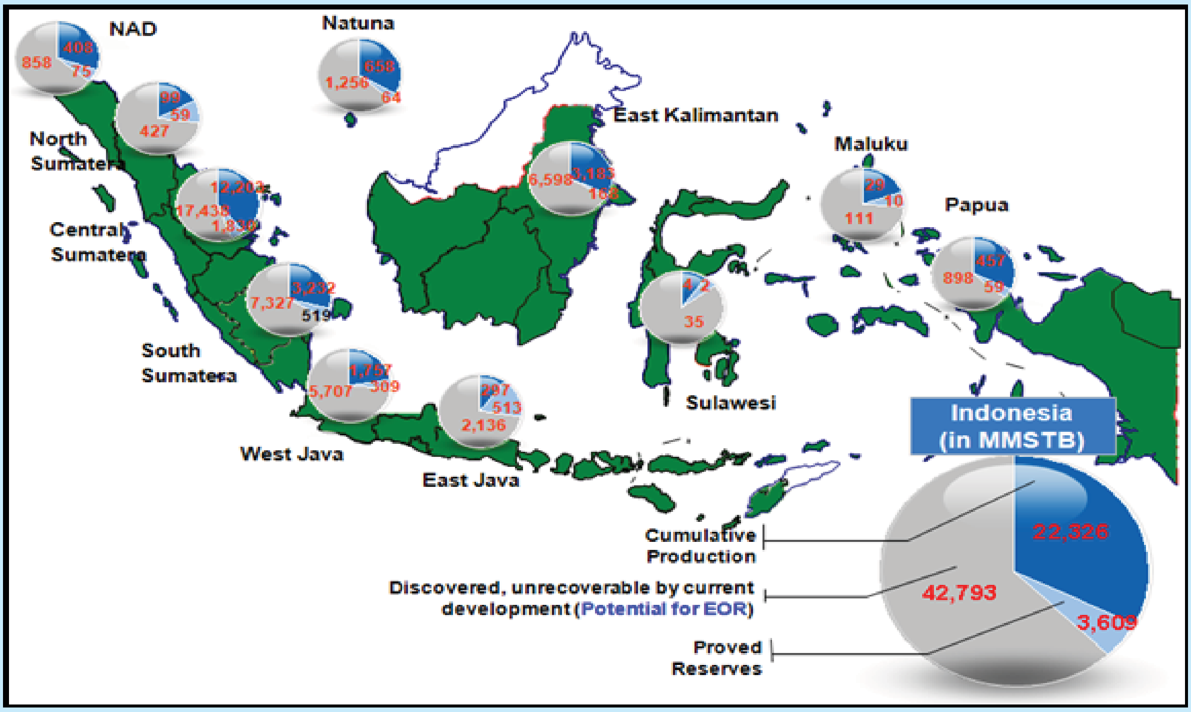

Figure 1
Theoretical potential of EOR in Indonesia as of January 1, 2010.
Theoretical EOR potential refers to an accumulation of discovered oil but enabled yet to be produced through the current technologies applied

potential in Indonesia[17]. It has also many large stationary sources of CO_2 from power generation and industrial activity that can be captured. Another important aspect is the existing gas pipeline transport network that could potentially fit into the CO_2 EOR sequestration operation. It would be advantageous to use the existing right of way to access depleted oil reservoirs.

This paper investigates the possibility of application CO_2 EOR sequestration in South Sumatra using a systematic approach specifically developed to integrate the CO_2 EOR sequestration chain. The detailed investigations include ranking of suitable CO_2 sources and sinks (reservoirs) by employing a set of criteria suits to the characteristics of South Sumatra and pairing of source and sink for CO_2 EOR sequestration pilot project. Results of this work are expected to accelerate the deployment of CO_2 EOR sequestration in Indonesia and provide the basis for further source-sink matching in another region in Indonesia.

II. METHODOLOGY

Method used in this work was defined systematically into three steps, selecting the best CO_2 sources, selecting the suitable sinks, and making links for source and sink.

A. CO_2 sources scoring and ranking

Selecting the best source is accomplished through data collecting and developing a list of criteria for scoring and ranking of CO_2 sources. This study focuses only on potential CO_2 sources that are technically amenable to CO_2 capture and transportation to oil fields for CO_2 injection. Unintentional releases of GHG emissions that occur during the extraction, processing, and delivery of fossil fuels to the point of final use, generally defined as fugitive emissions, were not taken into account for data collection in this work. The data inventory was executed through questionnaires given in Table 1 and interviews to the operators. The CO_2 emissions from stationary combustion were calculated using IPCC guidelines[7]. The source scoring and ranking methodology used 14 criteria listed in Table 2 that measure the suitability and compatibility with available CO_2 capture technologies. All criteria are not equally important. Each criterion is given a weight that reflects its relative importance among the set of criteria. The prospective CO_2 sources are then measured against each criterion which ranging from 0 (least desirable) to 10 (most desirable), indicating how well it measured on that particular criteria.

B. CO_2 EOR sequestration sinks scoring and ranking

Choosing the best sink comprises inventory of potential CO_2 EOR sites and its associated CO_2 storage capacity and proceeds with screening and ranking based on criteria specifically developed for CO_2 EOR sequestration. Only oil fields within 300 km were subject to the process of a ranking assessment to establish the best candidate. Due to confidential reason, the oil fields are indicated only by code. CO_2 EOR reservoir screening was performed using screening criteria provided in Table 3[15]. If resulted in miscible displacement, then assumed it can improve the additional recovery of oil as high as 12% of the OOIP but in case of immiscible, the additional recovery is only 5% of the OOIP[14]. CO_2 storage capacity associated with CO_2 sequestration was estimated by Eq. (1) using cumulative production and proved reserves data whilst the additional storage due to EOR is equivalent to that volume vacated by incremental oil recovery in shown by Eq. (2). RF miscibility is equal to 5% if the displacement is immiscible while 12% for miscible.

$$MCO_2 = d_{CO_2} \times B_o \times \left(V_{cumm.prod} + V_{proved}\right) \quad (1)$$

$$MCO_{2EOR} = \frac{\mathrm{OOIP}}{\mathrm{EUR}} \times RF_{miscibility} \times MCO_2 \quad (2)$$

The second phase was ranking the sinks using the criteria listed in Table 4. The application of the criteria is to evaluate the suitability of the sinks in terms of CO_2 EOR and CO_2 sequestration. The methodology was developed according to a set of criteria with corresponding assigned score for the reservoirs that has best suitability for CO_2 EOR and sequestration. Injectivity was calculated based using the gross average annual production and the number of wells per field to calculate a daily rate for pore space void age creation in tons of CO_2 per field per well. Risk was addressed by seal thickness, number of abandoned wells, contamination, willing partner

Table 1
Data questionnaire for assessing and scoring CO_2 sources

Data Type	Description
Data for selected CO_2 sources inventory	
Status	Example: Operating, Shutdown/Suspended
Fuel Type	Fuel source used that produces the CO_2. Example: Coal, Natural Gas, Heavy Oil, Naptha
Fuel Consumption Rate	The amount of fuel (coal, NG, oil) consumed in one year (tons/y, cubic feet/y, etc.).
Fuel Carbon Content	For coal, this would be tons of carbon per ton of coal fed to the power station boiler. For natural gas, this would be CO_2 content. Examples: 0.7 ton C per ton (coal)
CO_2 Emission	The most recent year CO_2 emission recorded, or for an average year (tons/y)
Installed/Plant Capacity	Electricity generation for power plant (MWe); Production capacity for other plant.
Flue Gas/Stream Volumetric Flow	Volumetric gas flow in the gas stream/flue gas from which the CO_2 would be captured (m^3/day)
Stream Temperature	The temperature of the CO_2 containing gas stream (^oC)
Pressure	Industrial streams vented pressure (Bar)
CO_2 Content	Example: 20% (by volume, dry basis)
Service Factor	Operating period of plant for one year which excludes downtime, such as maintenance, unplanned outages, reduced demand for products. Example: 80%
Variability	Variability on throughput and plant feedstock and fuels
Expected Working Life Time	The remaining working life of the facility (Years)
Data required for scoring candidate CO_2 sources	
Source Stream SO_x Concentration, ppmv (parts per million by volume)	
O_2 Concentration, %	
NO_x Concentration, ppmv	
Particulates Content, mg/Nm^3	
Trace Materials Content	
Implementation Date	
Existing Infrastructure	
Cooling Water Supply	

Table 2
Developed scoring system for assessing suitability and compatibility of CO_2 source

CRITERIA	Weight	SCORE			CRITERIA DESCRIPTION		
GENERAL WANTS		Low	Medium	High	Low	Medium	High
Source stream Concentration	50	0	-	10	≤ 3%	-	90-100%
CO2 volume per year	30	0	-	10	300,000	-	2 million
Source Stream SOx concentration	25	0	5	10	No FGD installed	Conventional FGD installed	Sweet natural gas & small Sox
O2 concentration	10	0	-	10	≥12%	-	≤ 3%
Nox Concentration	10	0	-	10	> 100 PPMv	-	< 10 PPMv
Particulates Content	10	0	-	10	Coal fuel & cement sources	-	Natural gas fuel sources
Trace Materials Content	10	0	-	10	Coal or other fuels & Trace gases that are constituents of air		Natural gas fuelled facilities
Implementation date	7	0	-	10	The oldest	-	The newest
Distance from attractive storage Location	15	0	-	10	> 100 km	-	Shortest distance among candidates
Existing Infrastructure	15	0	5	10	No infrastructure	Existing right-of-way	Existing high pressure pipeline
SOURCE SPECIFIC WANTS							
Power station supercritical	10	0	-	10	Subcritical	-	Supercritical
Cooling Water Supply	15	0		10	Seawater or none	-	Plentiful fresh water
Willing Partner	20	0	-	N/A	No	-	Yes
Space availability	15	0		10	Inadequate or no space	-	There is space

Table 3
Oil field data for CO_2 EOR screening and CO_2 storage capacity calculations

No	Fluid Characteristic and Reservoir Rock			CO_2 Flooding Screening Criteria	Remark
1	Reservoir Pore Volume	MM cf	5,185		Miscible Injection
2	Formation Thickness	ft	171		
3	Formation Type		-	Sand Stone / Lime Stone	
4	Reservoir Depth	ft, SS	5,720	> 2500	
5	Initial Reservoir Temperature	^{o}F	265		
6	Initial Reservoir Pressure	psig	2,767		
7	Current Reservoir Temperature	^{o}F		Not Critical	
8	Current Reservoir Pressure	psig			
9	Porosity	%	19.3		
10	Permeability	mD	407.0	Not Critical	
11	Water Saturation	%			
12	Oil Saturation	%		> 20 ↗ 55 ↗	
13	Gas Saturation	%			
14	Oil Formation Volume Factor	RB/STB	1.27		
15	Gas Formation Volume Factor	cuft/scf			
16	OOIP	MSTB	124,301		
17	Cummulative Production @31 Dec. 2009	MSTB	55,490		
18	Remaining Reserves @01 Jan. 2010	MSTB	1,690		
19	Estimated Ultimate Recovery (EUR)	MSTB	57,180		
20	Oil Gravity	^{o}API	35.4	> 22 ↗ 36 ↗	
21	Oil Viscosity	cp		< 10 ↘ 1.5 ↘	
22	CO_2 Density at P and T Reservoir	kg/m^3	353.7		
23	CO_2 Storage EUR	tonne	4,096,359		
24	CO_2 Storage EOR	tonne	1,068,587		
25	CO_2 Storage Total	tonne	5,164,945		
26	Additional Oil Recovery	MSTB	14,916		

↗ = Suggested for higher reservoir fluid characteristic
↘ = Suggested for lower reservoir fluid characteristic
55 = Average application of reservoir fluid characteristic

Table 4
Scoring system for CO_2 EOR sequestration sinks

No.	Criteria	Scores
1	Capacity: CO_2 storage	21 = full score down to 50 Mt; linear to 10 Mt.
2	Injectivity: CO_2 storage/day/well	10 = full score for oil fields; linear between high and low; If number of wells are unknown, then replace "/well" with "/field"
3	Injectivity: number of existing production and injectivity.wells	10; linear between high and low. If number of wells are unknown, then score is 0.
4	Confinement: seal thickness	16 = full score to 100 ft., linear between 100 and 15 ft.
5	Confinement: number of abandoned wells	4 = full score for zero abandoned wells
6	Contamination of other resources	4 = full score if no contamination by CO_2
7	Economics: EOR or other monetary offset	17 = EOR full score; other offset as assessed
8	Economics: Infrastructure	4 = full score for full useable infrastructure
9	Economics: Monitoring opportunity	4 = full score onshore, 0 if offshore
10	Economics: Availability - Depletion date	5 if 2015 or less, 0 if 2025 or greater, linear in between
11	Economics: Industry willing partner	5 as assessed
Total = 100		

Table 5
CO_2 emissions from selected industrial activities in South Sumatra region

CO_2 Source	Method	CO_2 (tonnes/year)
Power Plant (multiple sources)	Fuel Combustion (IPCC 2006) and Data Survey (2012)	1,786,062
Petroleum Refinery (single source)	Data Survey (2012)	619,527
Gas Gathering Station (single source)	Data Survey (2012)	132,754
Cement Plant (single source)	Data Survey (2012)	500,760
Fertilizer Plant (single source)	Data Survey (2012)	2,506,652
TOTAL		**5,545,755**

and date of depletion. The date of depletion was set to reward early commercial demo opportunities. Storage costs were addressed by offsets, existing infrastructure, and monitoring opportunity. At this stage, transport and capture costs of CO_2 were not considered.

C. Sources-sinks matching

Finally source and sink matching utilizes the short lists of independently scored and ranked sources and sinks established in the preceding steps. It focuses on establishing a dependable supply of CO_2 and transporting it to the sink. The source is ideally pure CO_2 or close to it. The sink is ideally a large depleted oil or gas reservoir where in the future the storage costs can be offset by producing the increased oil and gas reserves. The location for a CO_2 EOR sequestration pilot will need to have a large assessed capacity sink and produced economical amount of oil recovered because it will have direct relevance to larger-scale operations[(2)]. The resulting approach is to making links between source and sink. If more than two clearly defined opportunities still exist, consider the identified combinations using the following yardstick, rank the combinations by closeness to each other; the sources have been previously ranked by a number of factors need more detailed assessment; If more than two or three sink opportunities exist that are closely ranked, collect more detailed data and assess it (including reservoir modelling and economic evaluation) to obtain a final ranking.

III. RESULTS AND DISCUSSIONS

A. CO_2 sources scoring and ranking

As shown in Table 5, over 5.5 million metric tons of CO_2 are emitted each year from the sources considered in this work. The largest amount of CO_2 emitted from fertilizer plant, with an average annual emission of 2.5 Mt CO_2 per year. Identified major CO_2 point sources in South Sumatera include power plants, petroleum (refinery) and gas-processing facilities (gas gathering station-GGS), cement plants, and fertilizer-producing facilities. The GGS emerged as the most desirable capture source with a score more than double that of the second most attractive source as shown in Table 6. The facility's high ranking appears to have been the result of its (i) proximity to storage, (ii) high purity CO_2 stream from the GGS exhaust, (iii) relatively new built facility, and (iv) sufficient CO_2 to support a CO_2 EOR sequestration

Table 6
Score and ranking of CO_2 source for capture suitability

CRITERIA	Weight	GGS		Power Plant		Fertilizer Plant		Cement Plant		Petroleum Refinary	
GENERAL WANTS		Score	General	Score	General	Score	General	Score	General	Score	General
Source Concentration	50	10.0	500	1.4	72	1.0	48	1.8	89	0.9	47
CO_2 volume per year	30	0.0	0	8.7	261	2.4	71	1.2	35	1.9	56
Source SO_x concentration	25	10.0	250	0.0	0	0.0	0	0.0	0	0.0	0
O_2 concentration	10	10.0	100	9.1	91	10.0	100	1.0	10	0.8	8
NO_x Concentration	10	10.0	100	0.0	0	7.2	72	3.9	39	9.7	97
Particulates Content	10	10.0	100	0.0	0	10.0	100	0.0	0	8.0	80
Trace Materials Content	10	10.0	100	0.0	0	10.0	100	0.0	0	8.0	80
Implementation date	7	10.0	70	8.4	59	8.4	59	5.8	41	0.0	0
Distance from attractive storage Location	15	10.0	150	7.5	112	0.0	0	6.9	104	0.0	0
Existing Infrastructure	15	10.0	150	0.0	0	0.0	0	5.0	75	10.0	150
SOURCE SPECIFIC WANTS											
Power station supercritical	10	-	-	0.0	0	0.0	-	-	-	-	-
Cooling Water Supply	15	0.0	0	10.0	150	5.0	75	5.0	75	5.0	75
Willing Partner	20	5.0	100	0.0	0	0.0	0	0.0	0	0.0	0
Space availability	15	5.0	75	0.0	0	0.0	0	10.0	150	0.0	0
OVERAL RANKING SCORE		1695		745		626		617		593	

Table 7
Ranking of CO_2 EOR sequestration sinks

Rank	Oil Field	Distance from GGS (km)	EUR-CO_2 Storage Capacity	Total CO_2 Storage Capacity (EUR+EOR)	Ranking Criteria												TOTAL SCORE	
					Capacity		Injectivity		Confinement		Contamination of CO_2	Economics						
			Mt	Mt	EUR	EUR+EOR	2	3	4	5	6	7	8	9	10	11	EUR	EUR+EOR
1	H3	98.3	4.10	5.16	1.7	2.2	3.0	0	16	4	4	17	4	4	4.0	5	62.8	63.2
2	I2	120.4	3.70	4.25	1.6	1.8	10.0	0	16	4	4	17	4	4	2.3	0	62.8	63.1
3	F21	76.2	14.19	18.44	6.0	7.7	1.7	0	16	4	4	17	4	4	0.0	0	56.6	58.4
4	I1	118.6	2.78	3.13	1.2	1.3	6.3	0	16	4	4	17	4	4	1.5	0	58.0	58.2
5	A	26.6	0.42	0.57	0.2	0.2	3.8	0	16	4	4	17	4	4	5.0	0	58.0	58.0
6	G2	85.6	0.39	0.56	0.2	0.2	2.9	0	16	4	4	17	4	4	5.0	0	57.0	57.1
7	N1	221.3	0.81	1.20	0.3	0.5	4.2	0	16	4	4	17	4	4	1.5	0	55.0	55.1
8	H1	95.3	0.19	0.47	0.1	0.2	0.4	0	16	4	4	17	4	4	5.0	0	54.5	54.6
9	D7	59.6	6.95	7.92	2.9	3.3	1.8	0	16	4	4	17	4	4	0.0	0	53.7	54.1
10	L1	153.0	0.06	0.09	0.0	0.0	0.0	0	16	4	4	17	4	4	5.0	0	54.0	54.0
11	K1	142.0	0.01	0.07	0.0	0.0	0.0	0	16	4	4	17	4	4	5.0	0	54.0	54.0
12	K9	150.6	0.05	0.07	0.0	0.0	0.0	0	16	4	4	17	4	4	5.0	0	54.0	54.0
13	M2	191.3	0.00	0.01	0.0	0.0	0.0	0	16	4	4	17	4	4	5.0	0	54.0	54.0
14	I3	128.5	0.17	0.19	0.1	0.1	1.0	0	16	4	4	17	4	4	3.9	0	53.9	53.9
15	G3	88.8	0.08	0.11	0.0	0.0	0.3	0	16	4	4	17	4	4	4.1	0	53.5	53.5
16	D1	53.8	0.00	0.00	0.0	0.0	2.4	0	16	4	4	17	4	4	2.0	0	53.4	53.4
17	D3-D5	53.8	3.54	6.38	1.5	2.7	1.5	0	16	4	4	17	4	4	0.0	0	52.0	53.2
18	E3-E17	68.3	3.26	4.55	1.4	1.9	2.1	0	16	4	4	17	4	4	0.0	0	52.4	53.0
19	K2-K6	145.3	3.91	4.77	1.6	2.0	1.7	0	16	4	4	17	4	4	0.0	0	52.4	52.7
20	J6	139.3	0.95	1.24	0.4	0.5	0.2	0	16	4	4	17	4	4	2.6	0	52.2	52.3
21	F20	73.8	1.90	2.49	0.8	1.0	0.7	0	16	4	4	17	4	4	1.5	0	52.0	52.3
22	E1	64.1	1.57	2.31	0.7	1.0	0.5	0	16	4	4	17	4	4	1.3	0	51.5	51.8
23	H2	95.7	0.06	0.27	0.0	0.1	0.1	0	16	4	4	17	4	4	2.5	0	51.6	51.7
24	K7	148.0	0.65	0.87	0.3	0.4	0.5	0	16	4	4	17	4	4	1.8	0	51.6	51.7
25	B	33.1	2.32	3.53	1.0	1.5	1.0	0	16	4	4	17	4	4	0.0	0	51.0	51.5
26	D6	58.5	0.16	0.22	0.1	0.1	0.0	0	16	4	4	17	4	4	2.3	0	51.4	51.4
27	F28-F32	78.4	2.88	4.06	1.2	1.7	0.7	0	16	4	4	17	4	4	0.0	0	50.9	51.4
28	L3	168.0	1.38	1.67	0.6	0.7	1.7	0	16	4	4	17	4	4	0.0	0	51.2	51.4
29	L2	160.0	0.68	0.87	0.3	0.4	0.6	0	16	4	4	17	4	4	1.2	0	51.1	51.2
30	J1	132.5	0.08	0.09	0.0	0.0	0.1	0	16	4	4	17	4	4	1.9	0	51.0	51.0
31	J5	138.0	0.31	0.43	0.1	0.2	0.2	0	16	4	4	17	4	4	1.6	0	51.0	51.0
32	E2	68.1	2.38	3.13	1.0	1.3	0.6	0	16	4	4	17	4	4	0.0	0	50.6	51.0
33	C2-4	47.6	3.31	4.40	1.4	1.8	0.0	0	16	4	4	17	4	4	0.0	0	50.4	50.9
34	N2	236.4	0.39	0.45	0.2	0.2	1.6	0	16	4	4	17	4	4	0.0	0	50.8	50.8
35	F23-F27	76.6	1.41	1.96	0.6	0.8	0.9	0	16	4	4	17	4	4	0.0	0	50.4	50.7
36	F1-F18	72.0	1.31	1.87	0.5	0.8	0.9	0	16	4	4	17	4	4	0.0	0	50.4	50.7
37	F22	76.2	1.13	1.35	0.5	0.6	0.8	0	16	4	4	17	4	4	0.0	0	50.2	50.3
38	J2-J3	133.4	0.08	0.84	0.0	0.4	0.9	0	16	4	4	17	4	4	0.0	0	49.9	50.3
39	F19	73.2	0.53	0.68	0.2	0.3	0.4	0	16	4	4	17	4	4	0.0	0	49.6	49.7
40	E18	69.4	0.39	0.48	0.2	0.2	0.3	0	16	4	4	17	4	4	0.0	0	49.5	49.5
41	J4	137.2	0.38	0.43	0.2	0.2	0.2	0	16	4	4	17	4	4	0.0	0	49.4	49.4
42	G1	83.3	0.11	0.14	0.0	0.1	0.3	0	16	4	4	17	4	4	0.0	0	49.4	49.4
43	O1	290.0	0.15	0.24	0.1	0.1	0.3	0	16	4	4	17	4	4	0.0	0	49.3	49.4
44	N4	248.9	0.09	0.10	0.0	0.0	0.3	0	16	4	4	17	4	4	0.0	0	49.3	49.3
45	C1	44.5	0.11	0.16	0.0	0.1	0.0	0	16	4	4	17	4	4	0.0	0	49.1	49.1
46	O2	460.6	0.00	0.00	0.0	0.0	0.0	0	16	4	4	17	4	4	0.0	0	49.0	49.1
47	K8	150.0	0.04	0.05	0.0	0.0	0.0	0	16	4	4	17	4	4	0.0	0	49.0	49.0
48	D2	53.8	0.01	0.01	0.0	0.0	0.0	0	16	4	4	0	4	4	1.3	0	33.3	33.3
49	M1	180.0	0.00	0.00	0.0	0.0	0.0	0	16	4	4	0	4	4	0.0	0	32.0	32.0
50	N3	241.5	0.00	0.00	0.0	0.0	0.0	0	16	4	4	0	4	4	0.0	0	32.0	32.0

pilot project, which can be further increased to meet the requirements for larger demonstration project (500–2,500t/d CO_2) by reducing the temperature of the raw gas feed to the amine absorber to the plant's original design specifications.

The power plant is ranked second with overall final score on source suitability is almost half of that of GGS. CO_2 concentration in its flue gas, 16.8%, is relatively low compared to GGS. This indicates higher cost per ton of CO_2 captured. From the point of view of space availability, retrofitting CO_2 capture would be a major challenge because the plant is already congested. This power plant has two major units that came on stream at different times. Only one pair is relatively new with the construction and potential to be fitted with CO_2 capture facilities for longer working lifetime. Addition of CO_2 capture facilities requires a substantial amount of water, which appears not to be an issue for this power plant. Located near the river, this power plant utilizes abundant fresh water from the river currently both for supplying the cooling towers and as make up water. However, the fact that these units are subcritical makes it far less attractive and more challenging as a source for CO_2. The third, fourth, and fifth ranked CO_2 sources are fertilizer plant, cement plant, and petroleum refinery, respectively. Fertilizer plant may move up in ranking if future plans to expand and use coal as an energy source come to fruition. In this eventuality, there will then be a pure CO_2 stream produced in excess of the requirements for urea production.

The ranking analysis also revealed that many of the existing limitations on CO_2 capture from the sources could be overcome in the future with changes to their operations, retrofit, or modernization. This reconfirmed the hypothesis that South Sumatra would continue to have good availability of CO_2 capture sources into the future.

B. CO_2EOR sequestration sinks scoring and ranking

Scouting work identified 98 oil fields that comprise of 581 reservoirs within the South Sumatra basin representing 59% of total OOIP in South Sumatra. These oil fields underwent the similar process to determining the most suitable CO_2 source. They were subjected to score and rank according to their suitability for CO_2 EOR and CO_2 sequestration using the method previously discussed in methodology section. Initial ranking that have been completed for the 95 oil field showed scores (out of 100) range from 32.0 to over 63.2 as tabulated in Table 7. In the second round of scoring, cutoff values for EOR incremental recovery, CO_2 storage capacity, and distance from GGS were used for individual fields. Only oil fields within 150 km distance from GGS and have produced more than one million barrels of oil at estimated ultimate recovery (EUR) were considered. This cutoff roughly equates to an incremental storage capacity of 0.1 Mt CO_2. Applying this process to Table 7, oil fields N1, L1, K1, K9, M2, G3, and D1

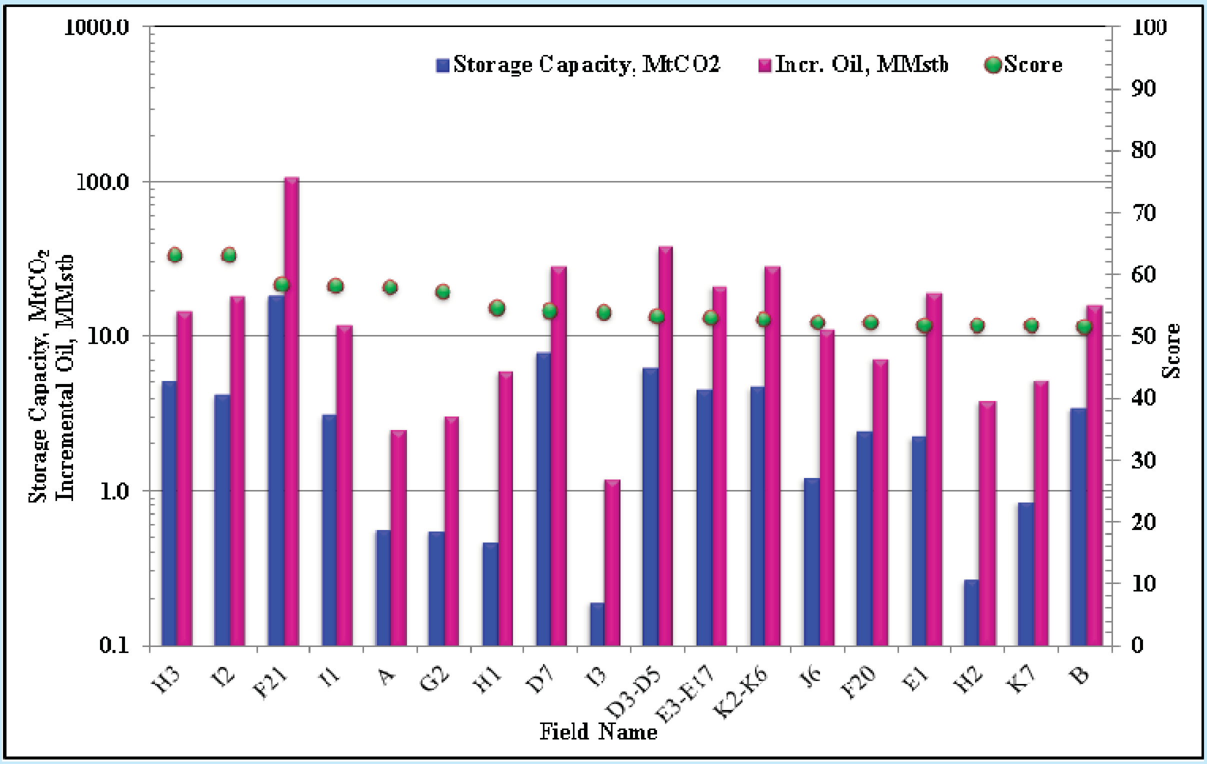

Figure 2
Scoring, incremental oil, and storage capacity for the top 20 oil fields CO_2 EOR candidates

are discarded from the top 25 oil field candidates for CO_2 EOR sequestration, and the remaining top 18 candidates are plotted by score, incremental oil, and storage capacity in Figure 2.

The two highest scoring fields are oil fields H3 and I2 due to their promise of incremental CO_2-EOR recovery. I2 has the highest injectivity for any oil field while H3 is the only oil field which has a willing partner at the present time in which the operator planned to apply CO_2-EOR in this field. Higher injectivity reflects the ability to handle high injection rate of CO_2 and the less number of wells required(3,5,12). So that, I2 is attractive in terms of to meet the capture rate of CO_2 emitted by the industrial sources. Oil field F21 is ranked third with the largest storage capacity of 18 Mt CO_2 while the two highest ranked oil fields have storage capacities of approximately 5 MT CO_2 each. The second highest storage capacity is for D7 at 8 Mt CO_2, ranked ninth in scoring. Oil field ranked in fourth may move up in ranking if there is willing partner. The score range among the oil fields is relatively close because several criteria have been assumed. For instance, confinement criteria were assumed due to inadequate data availability, particularly for seal thickness. It is assumed that this criterion is always satisfied since the field has acted as a trap for oil and gas for millions of years. It is also assumed that all of the oil fields do not have active faults since the field has acted as a trap for oil and gas for millions of years.

Grouping the oil fields relative to the proximity (Figure 3) shows the largest cumulative incremental oil and storage capacities (approximately 60%) are found in an area within 30 km of each other, 51–80 distance km from GGS. Of the examined oil fields, there of 77 fields would achieve miscible processes, 18 fields would immiscible, and the remaining were screened out because the oil too light and or the reservoirs too shallow. The opportunity of oil recoverable is approximately 480 MMstb and the potential CO_2 storage capacity is about 92 megatons (Mt) consists of 70 Mt for voidage replacement by

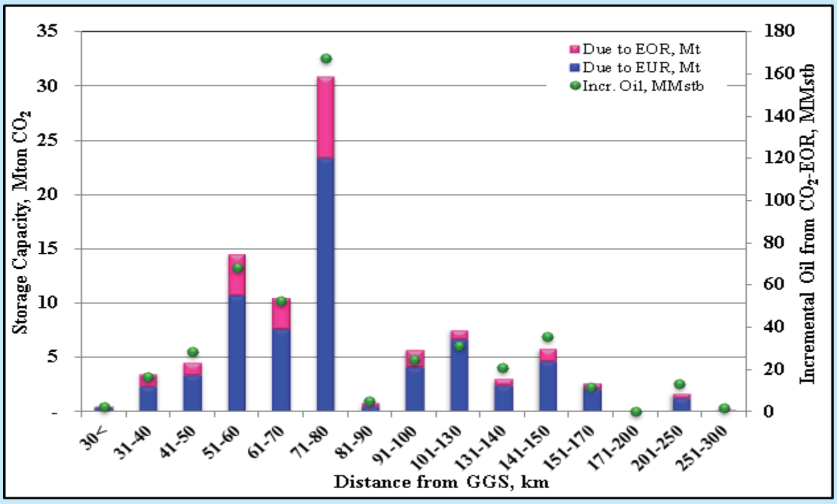

Figure 3
Potential incremental oil andestimated storage capacity from oil fields assessed

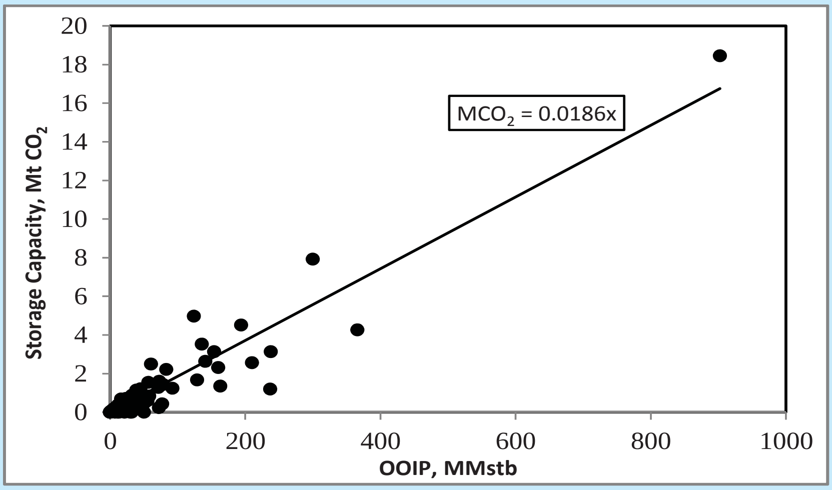

Figure 4
Correlation of storage capacity versus OOIP for South Sumatra basin

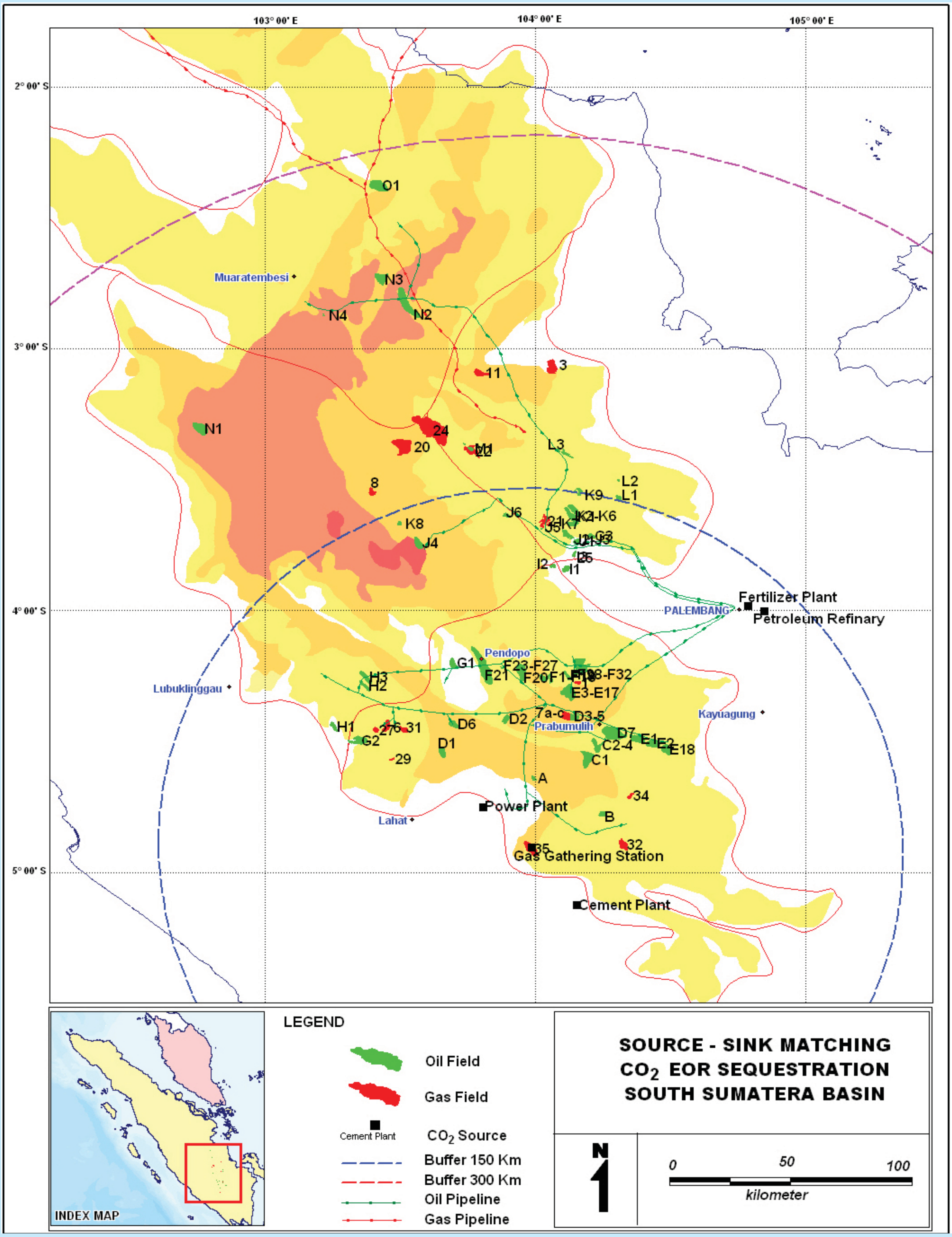

Figure 5
Source-sink matching for CO_2 EOR sequestration pilot project in South Sumatra basin

producing at EUR and additional 22 Mt at EOR. From the storage inventory created in this study, it is possible to correlate the CO_2 storage resource with the volume of OOIP leading to linear best fit curve as depicted in Figure 4. The derived correlation could be employed at regional level of South Sumatra basin.

C. Sources-sinks matching

The process of matching CO_2 source and oil fields (sinks) is accomplished with less mathematical analysis than the base processes of establishing the best sources and sinks, which is independent of their proximity to each other. Oil fields that have been ranked are matched to CO_2 source from GGS by plotting into geographical information system (GIS) on Map Info platform in Figure 5.

The GGS is an attractive CO_2 source. It can supply 0.13MtCO_2 per year which is enough for a commercial EOR operation and more than enough for a pilot CO_2 EOR sequestration project with typical injection rate 50–100 tons CO_2 per day. Some of the other sources have to be identified as the primary source if this project will be scaled up to a commercial storage operation of at least 1 Mt CO_2 stored annually. Fortunately, the other sources except for some of the gas-processing plants are within 150 km of GGS.

The most attractive sinks pilot in the South Sumatra would be in an oil reservoir where the commercial opportunity for CO_2 EOR exists and which could subsequently transition to storage. The three top oil fields for CO_2 EOR pilot are H3, I2, and F21. The H3 oil field has scored the highest (63.2 out of 100) for storage of all the oil followed closely by I2. With its current storage capacity, H3 is able to stored CO_2 produced from GGS in almost 40 years. The longer CO_2 sequestration operation is oil field F21, with more than a century operation and might be prolonged due to poorer injectivity.

Since transportation of the CO_2 is taken into account in the source-sink matching process, therefore, 2 pairs are generated. First option, the CO_2 source will be supplied from GGS and H3 will be the sink. Alternative option is the source remains the same but the oil field will be the sink. The latter option ensures the long term and large scale deployment of CO_2-EOR CO_2 sequestration. Oil field I2 is discarded in the matching process due to have longer distance of 120 km from the GGS as a result has less economic benefits. The mode of transportation would be by truck as the building of a pipeline cannot be justified for these low quantities of CO_2. If the pilot is successful, then a demonstration would be justified and a pipeline would be required to transport the CO_2.

IV. CONCLUSIONS

A systematic source-to-sink matching approach to pair industrial CO_2 sources with oil fields was successfully developed and generated source-sink pairs. This approach measures the suitability and compatibility of CO_2 sources in South Sumatra with available CO_2 capture technologies and enables rapid screening and evaluation for very large numbers of reservoirs in South Sumatera basin.

The GGS has the highest suitability as a CO_2 source for an early CO_2 EOR sequestration pilot scale with the ability to supply around 0.13 MtCO_2 per year.The H3 oil field has the highest rank in the sink scoringas is the only field has a willing partner at the present time to apply CO_2-EOR. The I2 oil fields is a close second in ranking and has the highest injectivity while F21, ranked in third, has the highest storage capacity of 18 Mt CO_2.

Application of source-sink matching in South Sumatra identified two potential pairs of source-sink candidates. It is suggested thatpair of GGS and H3 oil field be selected for pilot purposes due to an inexpensive CO_2 source and highest suitability for CO_2 EOR sequestration. Alternative option is a pair of GGS and F21 oil field. This pair has a large EOR potential and sufficient CO_2 storage capacity for commercial storage in the future and relatively closes each other.

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