THE FIRST IN-DEPTH ASSESSMENT OF CARBON CAPTURE UTILIZATION AND SEQUESTRATION (CCUS) FOR CO_2 MANAGEMENT OF SOUTH SUMATERA SNG PLANT

KAJIAN MENDALAM *CARBON CAPTURE UTILIZATION AND SEQUESTRATION* (CCUS) UNTUK PENGELOLAAN EMISI CO_2 PADA PABRIK SNG DI SUMATERA SELATAN

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ABSTRAK

Pabrik komersial SNG (*substitute natural gas*) yang menggunakan batu bara peringkat rendah sedang direncanakan untuk dibangun di daerah Pendopo, Sumatera Selatan. Hasil konversi batu bara menjadi gas tersebut menghasilkan emisi CO_2 antropogenik yang tidak boleh dilepaskan ke atmosfer dan harus dikelola dengan seksama. Dari berbagai cara, yang paling efektif adalah dengan pemanfaatan untuk keperluan peningkatan pengurasan minyak tahap lanjut pada lapangan-lapagan minyak tua (*Enhanced Oil recovery*-EOR) melalui injeksi CO_2 atau dengan sekuestrasi CO_2. Kajian ini bertujuan untuk menyelidiki potensi aplikasi dan kesiapan *implementasi carbon capture utilization and sequestration* (CCUS) untuk pengelolaan emisi CO_2 pada Pabrik SNG di Sumatera Selatan. Makalah ini mengulas prosedur pemeringkatan reservoir yang sesuai untuk aplikasi CCUS, penentuan profil injeksi, konsep pengelompokan (*clustering*) lapangan minyak yang dapat mengakomodasi pasokan CO_2 dalam waktu tahunan, perencanaan dan realisasi jalur perpipaan serta kemungkinan untuk penggunaan infrastruktur yang ada. Hasilnya menunjukkan bahwa lapangan minyak A1 memiliki peringkat tertinggi dalam *sink scoring* yang mana mengindikasikan tingkat kesesuaian yang tinggi untuk aplikasi CO_2 EOR dan sekuestrasi CO_2. Kemudian, terbentuk 3 *cluster* yaitu utara, tenggara dan barat sebagai basis pengembangan jaringan perpipaan lebih lanjut untuk transportasi CO_2. Potensi penyimpanan CO_2 terbesar berada di *cluster* tenggara dengan kapasitas simpan sebesar 27 $MtCO_2$. Pada penelitian ini pula, telah berhasil dikembangkan strategi injeksi untuk mengelola emisi CO_2 yang dihasilkan dari Pabrik SNG.

Kata kunci: *Carbon capture utilization and sequestration* (CCUS), pengelolaan emisi CO_2, Pabrik SNG Sumatera Selatan

ABSTRACT

A commercial low-rank coal SNG (substitute natural gas) plant is being planned to build in Pendopo, South Sumatra. However, the CO_2 produced is not allowed to be vented and should be managed properly. One approach to manage this anthropogenic CO_2 emission is through the utilization for CO_2 EOR (enhanced oil recovery) or CO_2 sequestration. This workaims to investigate the possibility of application and the readiness carbon capture utilization and sequestration (CCUS) for CO_2 management of South Sumatera SNG Plant. It presents technical ranking of suitable reservoirs, injection profiles determination, cluster principle of oil fields that can accommodate the amount of CO_2 supplied for a number of years, and planning and realization of trunk pipelines and the possibility to reuse the major part of the present infrastructure. The results show the A1 oil field has the highest rank in the sink scoring indicating that this field has highest suitability for CO_2 EOR application and CO_2 sequestration. Three clusters are formed, north, southeast and west cluster *as the basis to establish pipelines network development. The largest CO_2 storage potential is in southeast cluster, 27 MtCO_2 and the injection strategy developed is successful to manage CO_2 supply from SNG Plant.*

Keywords: *Carbon capture utilization and sequestration (CCUS), CO_2 management, South Sumatera SNG Plant*

I.INTRODUCTION

A commercial low-rank coal SNG (substitute natural gas) plant is being planned to build in Pendopo, South Sumatra. However, this coal gasification processes will not only produce natural gas but also additional CO_2. This CO_2 production is not allowed to be released directly in to the atmosphere but it should be managed properly. One approach to manage this anthropogenic CO_2 emission is through the utilization for CO_2 EOR (enhanced oil recovery) or CO_2 sequestration. Means to manage CO_2 via EOR operations is the most attractive because it contributes to the recovery of additional oil while providing a secure geological trap with the fact that the reservoir held oil in place for millions of years (Utomo and Usman, 2011). In a future carbon-constrained environment where efforts in reducing greenhouse gas is becoming intense, CO_2 sequestration will probably become the preferred emission abatement option and more reservoirs may be considered suitable for CO_2 sequestration (Jerry and Stefan, 2002; Massachusetts Institute of Technology, 2010; IPCC, 2006). Moreover, an additional advantage in using CO_2 EOR for managing CO_2 emissions is the use of an already-existing infrastructure and knowledge base.

In South Sumatera excellent opportunities exist for CO_2-EOR application or CO_2 sequestration because of the availability of many depleted oil reservoirs (Utomo and Usman, 2011; Usman, 2011,). The opportunities may take advantage of the fact that in time part of the existing gas infrastructure may become available for transport of the captured CO_2 from the SNG plant. However, not all oil reservoirs are suitable for CO_2-EOR for various technical and economic reasons (Jerry and Stefan, 2002; Manrique, 2007). Although the EOR technology is readily available (Don and Willhite, 2003; Advanced Resources International, 2011), preliminary issues that need to be addressed include: 1) screening for EOR suitability; 2) potential oil recovered and CO_2 storage capacity and; 3) technical ranking of suitable reservoirs. The two first issues have been addressed in the previous study (LEMIGAS, 2011). The study rendered a lot of valuable information about the potential application of CO_2 EOR including the suitability of oil fields, oil recovered, and CO_2 sequestration opportunities. Pendopo area which has been selected as the location of SNG plant will be the main source of CO_2. Oil fields within 100 km radius from this area, most of which are in an advanced stage of production, constitute a prime target for CO_2 EOR and sequestration.

At this stage, the development of CO_2 EOR and sequestration in South Sumatra requires infrastructures that enable delivering CO_2 from the SNG plant to the nearby oil fields. As a SNG Company running a large point source of CO_2 wishes to have sufficient certainty as to the availability of CO_2 required and storage and injection capacity, before investing in expensive capture installations and transport facilities (purification, compression and flow lines). The company may wish to have a (long term) contract with other parties to provide these services. The contract then would pertain to either a batch or continuous supply of CO_2 (4-5 Mton) (Mitsubishi Heavy Industries, 2012) to be used for EOR or stored during the life cycle of the installations that generate and capture CO_2.

Therefore, building the infrastructure for CO_2 transportation needs robust assessment of which the order of reservoirs will be connected with the pipeline networks as it will justify the required investment and lower the cost per ton of transported CO_2 as well as to ensure the project lifespan is long enough. The decision making should also be supported by the need for a master plan to be able to supply constant CO_2 for injection at a certain level ofton CO_2 per year over a long period of time (DHV, 2009). This is achieved by making an injection development plan and robust scheduling of the various injectionpoints within (clustered) oil fields is required to minimize costs and efficient pipeline networks development to exactly match the supply.

For this purpose an investigation was carried out that focused on the technical ranking of suitable reservoirs, injection profiles determination, cluster principle of oil fields that can accommodate the amount of CO_2 supplied for a number of years, planning and realization of trunk pipelines and the possibility to reuse the major part of the present infrastructure, i.e. interfield pipelines.

II. METHODOLOGY

A. Data Acquisition

The data for the assessment were primarily extracted from LEMIGAS database and if necessary completed by the operators. The latter was executed through questionnaires which have been performed in the previous study (LEMIGAS, 2011; ADB and LEMIGAS, 2012). Since not all of the data is completed, the data is reviewed to assess its compliance with quality objectives and also for consistency, completeness, and accuracy. In some cases, some data have to be generated through calculation and a well-founded assumption. Data in the report are published only in an aggregated form to safeguard confidentiality.

B. Scoring and Ranking

The scoring methodology is developed according to a set of criteria with corresponding assigned score for the reservoirs that has best suitability for CO_2 EOR and sequestration (ADB and LEMIGAS, 2012; Jerry and Stefan, 2002; Sugihardjo *et al*., 2012; Taber, *et al*., 1977). The method enables rapid screening and evaluation for very large numbers of reservoirs in surrounding Pendopo based on reservoir fluid properties, incremental oil produced, and CO_2 sequestration performance.

Once all of the required data were obtained, the reservoirs are scored and ranked using the scoring system. The final score can then be used to rank the reservoirs by relative suitability. This ranking may be used at least as a preliminary method for identifying the potential field candidates. Application of these criteria can be applied to other types of CO_2 EOR and sequestration options. However, depending on the type of option, the list might be expanded or changed if further analysis suggested it is necessary to suit the specific circumstances of a proposed CO_2-EOR and sequestration project. The criteria and associated indicator is described in Table 1. below.

Reservoirs have various degrees of suitability for CO_2 EOR and sequestration on the basis of intrinsic reservoir and oil characteristics, and they can be accordingly ranked using this method. This ranking is based on determining, for each reservoir property, a corresponding parameter by comparison with fictitious best (optimum) and worst (not suited) reservoirs for CO_2 EOR and sequestration operations (ADB and LEMIGAS, 2012; Sugihardjo *et al*., 2012; Taber *et al*., 1977).

The criteria of reservoir depth and oil viscosity can be ignored because two other parameters, oil gravity and reservoir temperature, either affect or are affected by the former two (i.e., temperature is affected by reservoir depth, and oil viscosity is affected by oil gravity). Thus, depth and oil viscosity do not necessarily need to be explicitly considered in reservoir scoring for CO_2 EOR and sequestration as they have represented by these two parameters. Other criterion such as permeability is not a critical because most oil reservoirs that have sufficient production should also have adequate CO_2 injectivity (Jerry and Stefan, 2002; CO_2 CRC, 2008).

C. Source-sink Matching

The process of matching CO_2 source and oil fields (sinks) can be accomplished with less mathematical analysis than the base processes of establishing the best sinks, which is independent of their proximity to each other. The SNG Plant along with oil fields is plotted on the Map Info platform. The next step is to evaluate the distance between the source and sinks and to establish the pipeline route. 100 km circle radius is drawn around the SNG Plant as point source. Only oil fields identified within 100 km will be matched to CO_2 produced from SNG plant.

The concept of realization of pipeline is based top 20 oil fields ranking. Trunk pipeline is laid within top 20 oil fields. This will ensure the most optimum distribution reaching lower suitability oil fields if in the future there will be an expansion by connecting the flow line to the adjacent oil fields. Therefore, grouping fields into cluster is needed to deliver this objective. Clusters are composed of groups of oil fields that have higher suitability for CO_2 EOR and CO_2 sequestration (TNO, 2008). With respect to long term and large scale deployment of CO_2 EOR and sequestration, a cluster should at least contain a few 'core' fields (contained in top 20), that – in

Table 1
Methodology for Scoring Oil Fields for CO_2 EOR and Sequestration

No.	Criteria	Scores	Remarks*
1	CO_2 storage capacity	▪ 16= full score down to 50 Mt; ▪ Linear to 10 Mt.	Field based criterion; if satellite fields existed nearby that satisfied this criterion or the cumulative storage capacity of several fields in close proximity satisfy this criterion
2	Injectivity: CO_2 storage/day	▪ 9 = full score for oil fields; ▪ Linear between high & low; ▪ Production based	Injectivity (using production rate as a measure) is based on rate of created CO_2 storage/field for oil. The actual magnitude of the injection rate for CO_2 is expected to be greater. For this analysis, the injection rate for CO_2 in oil reservoirs is assumed to be 10 times greater than the CO_2 storage creation rate.
3	Injectivity: CO_2 storage/day/well	▪ 9 = full score; ▪ Linear between high & low	Each well, that can be used for injection, increases the cumulative injection rate.
4	Seal thickness	▪ 9 = full score to 100 ft; ▪ Linear between 100 & 15ft.	Scoring using the ratio between the thickness or percentage of sandstone and that of shale in a geologic section for South Sumatra is 60:40.
5	Number of abandoned wells	▪ 3 = full score for zero abandoned wells	Takes account of the risk of leakage due to the "pin pricks" through the reservoirs created by drilling.
6	Contamination of other resources	▪ 3 = full score if no contamination by CO_2	The concern is that the storage may devalue other resources (e.g., potable water, oil, gas, etc.) that have not been fully exploited yet.
7	Infrastructure	▪ 3 = full score for full useable infrastructure	All the depleted oil and gas fields have extensive infrastructure.
8	Availability: Depletion date	▪ 4 if 2015 or less; ▪ 0 if 2025 or greater; ▪ Linear in between.	This analysis is based on average properties for oil fields. Since each field consists of multiple reservoirs, the depletion date for the each field is a maximum as it represents the date of the last reservoir to be depleted. All other reservoir will be depleted. Depending on the purpose of the assessment, the scoring attributes may change.
9	Economics: Industry willing partner	▪ 5 as assessed.	This is a critical component as the dedication of both money and expertise are needed.
10	API gravity	▪ 5 = full score to 48 (^{o}) ▪ Linear between 48 &27 (^{o}).	A measure of how heavy or light petroleum liquid is compared to water. If its API gravity is greater, it is lighter and floats on water; if less, it is heavier and sinks.
11	Oil saturation	▪ 9 = full score to 60% ▪ Linear between 60 & 25%.	The oil saturation is the fraction of the pore space occupied by oil. The oil saturation directly affects the amount of recoverable reserves.
12	Pressure/MMP	▪ 9 = miscible ▪ 4.5 = immiscible ▪ 0 = failed.	Miscibility in reservoir conditions determines the displacement efficiency. For this case, 16% RF is used for miscible flooding while immiscible flooding uses 5% RF.
13	Additional recoverable oil	▪ 16= full score; ▪ Linear between high & low.	The total estimated amount of oil in an oil reservoir, including both producible and non-producible oil, is called oil in place.
	Total = 100		

combination - can carry the larger part of the required constant CO_2 supply and injection and capacity over several years.

D. CO_2 Injection Profile for CO_2 EOR

For this study, a 'fast' Excel based model has been developed to calculate a CO_2 injection profile for given reservoir conditions (incremental oil recovery from EOR) in order to model the future CO_2 schedule and program. Injection profiles are calculated for top 20 oil fields contained in three clusters, west, southeast and north for describing a scheme of CO_2 demand to produce the residual oil left in depleted oil fields. Simulation results from X Oil Field is decided as a base case to generate the injection profile for other top 20 oil fields as shown in the Table 2.

Gross CO_2 utilization is defined as the cumulative gross CO_2 volume injected divided by the volume of incremental oil produced as a direct result of the injected CO_2. This CO_2 EOR incremental oil would not be produced at this time if CO_2 EOR were not implemented. The number provided, 10.74Mcf/stb, is close to the average field experience of CO_2 EOR project in North America; (John and Bill, 2010). The period of injection from the simulation is 10 years and also applied for top 20 oil fields in the clusters. These parameters also provide the basis on determining each injection rate for oil fields.

Some assumptions are made to enable generating the CO_2 injection profile for each cluster as follows:

- An injection well in a field is assumed not characterized by vertical depth and tubing size.
- The CO_2 will effectively flood the residual oil saturation to the producer well.
- Miscibility is defined from the screening results.
- Each oil field would completely be depleted to recover its residual oil.
- For the calculation of the injection profiles, depletion at plateau CO_2 injection rate is assumed.
- The degree of recovering in this case is defined as 10.74 Mcf/stb.

E. CO_2 Injection Profile for CO_2 Sequestration

The concept for CO_2 injection profile for CO_2 sequestrationis assumed that after fields has undergone depletion due to CO_2 flooding, the fields will be converted completely as CO_2 sequestration. Similar to injection profiles for CO_2 EOR, injection rate of top 20 oil fields contained in three clusters are calculated for describing a scheme for filling the depleted oil fields which in this case the reservoir is represented as a 'tank'. Unlike injection profile for EOR, rate here is defined as CO_2 filling rate to store the CO_2 utilizing reservoir full potential capacity. Using X Oil Field as the base case and some following assumptions, the injection profile for CO_2 sequestration can be generated.

- An injection well in a field is assumed not characterized by vertical depth and tubing size.
- There is not a temperature, pressure build up and hence density depth does not affect the profile along the well.
- Pressure losses due to friction are neglected.
- The reservoir pressure has not been constrained at the original oil field pressure.
- Each oil field would be filled to its original oil pressure.
- For the calculation of the injection profiles a filling at plateau rate is assumed. The degree of filling in this case is defined as 100%.
- Filling a reservoir will not gradually increase the reservoir pressure. Nevertheless, the maximum injection pressure and the maximum reservoir pressure dictate the actual degree of filling of a reservoir.

Table 2
X Oil Field as Base Case for Injection Profile

Base Case				
# Injector	Incremental Recovery (stb)	Rate (Mscfd/well)	Total Injection Rate (Mscfd)	Gross CO_2 Utilization (Mcf/stb)
6	6,119,768	3,000	18,000	10.74

For this case, individual field profiles have been adjusted to exactly match the CO_2 supply from SNG plant. The main goal here is to demonstrate that in principle a cluster can accommodate the assumed amount of CO_2 supplied for a number of years. It also shows at what time scale a next cluster will have to be developed for continuity reasons. As a consequence the CO_2 infrastructure will have to be expanded in due time.

III. RESULT AND DISCUSSION

A. Ranking of Oil Fields

The method developed and described previously for scoring and ranking a large number of oil reservoirs for CO_2 flooding suitability and CO_2 sequestration was applied to 93 oil fields. Screening results 43 oil fields have oil gravity within the recommended range of 27 – 48°API (Don and Willhite, 2003; Taber *et al.*, 1977). This is very important criterion and generally recommended to be greater than 27°API (light oils with density < 900 kg/m^3),but less than 48°API, because extremely light oil such as condensate is not conducive to the development of multicontact miscibility for miscible flooding (Jerry and Stefan, 2002). Oil viscosity is not a necessary screening parameter, since it is dependent on the oil gravity and reservoir temperature. To ensure an economic outcome for CO_2 EOR, the fraction of remaining oil before CO_2 flooding (Sor> 0.25) should be a limiting factor. Of these 47 oil fields meet this criterion (Babadagli, 2006). This criterion may be relaxed in the future, if the primary objective is CO_2 sequestration only rather than additional oil production. In terms of the storage capacity, none of the oil fields has the storage capacity of 50 $MtCO_2$ or greater. Only one field exceeds the minimum criterion of capacity, 10 $MtCO_2$. Miscibility also reflects the higher amount of CO_2 required for CO_2 EOR project, of remaining 52 oil fields satisfy this criterion.

Initial ranking have been completed for the 93 oil fields examined. Scores (out of 100) range from 9.0 to over 47.8. The top 20 oil fields (sinks) ranking arelisted in Table 3. The summary of top 20 oil fields versus storage capacity and additional recovery is depicted in Figure 1.

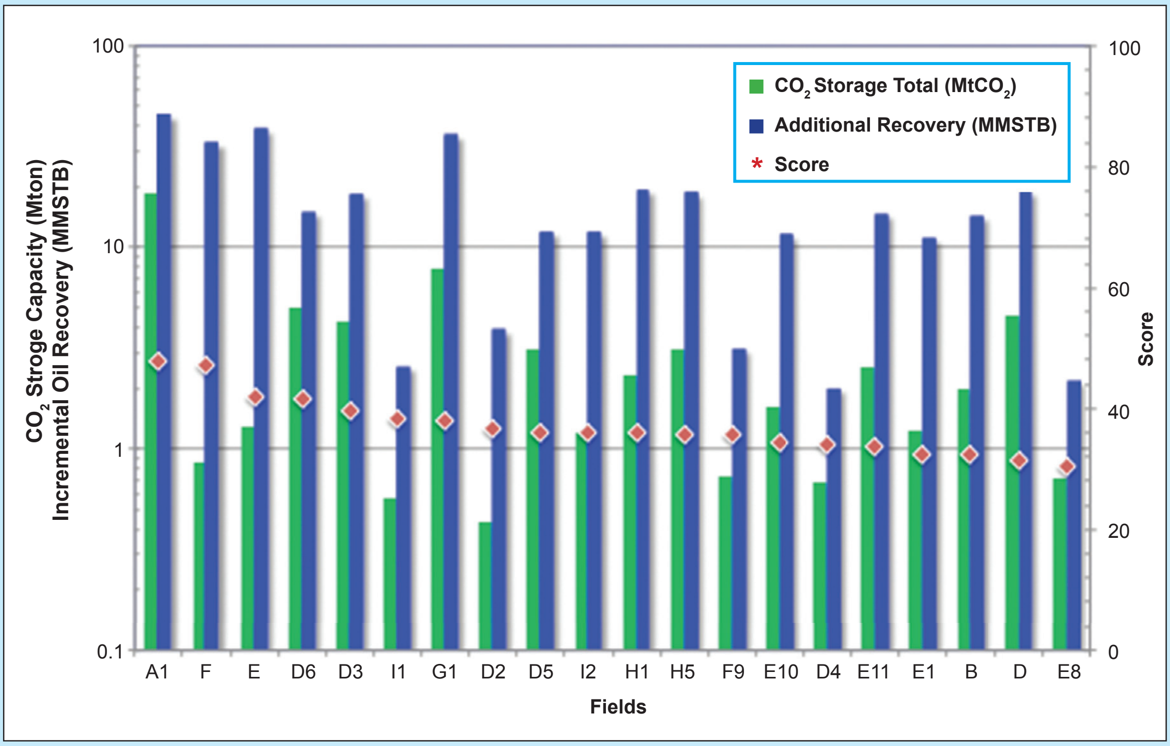

Figure 1
Storage Capacity, Scoring and Additional Oil Recovery for the Top 20 Oil Fields

Table 3
The Top 20 Oil Fields Ranking Relative to Proximity

Ranking	Fields Name	Distance From Pendopo (km)	OOIP (MSTB)	Storage Capacity Total (ton)	Additional Recoverable Oil (MSTB)
1	A1	13.8	902,405	18,441,682.00	45,120.23
2	F	69.7	273,300	865,347.00	32,796.00
3	E	20.00	321,064	1,276,226.30	38,527.68
4	D6	63.7	124,301	4,968,752.00	14,916.12
5	D3	49.00	366,000	4,253,415.00	18,300.00
6	I1	168.2	21,218	574,749.60	2,546.16
7	G4	101.8	300,000	7,918,000.50	36,000.00
8	D2	71.2	77,260	429,544.00	3,863.00
9	D5	48.3	237,946	3,130,973.90	11,897.30
10	I2	160.4	236,830	1,199,134.30	11,841.50
11	H1	96.9	160,357	2,312,435.40	19,242.89
12	H5	63.3	154,094	3,126,618.00	18,491.28
13	F9	80.7	25,910	729,936.00	3,109.20
14	E10	36.6	96,000	1,600,541.30	11,520.00
15	D4	16.1	16,551	680,683.10	1,986.13
16	E11	36.6	122,000	2,559,358.40	14,640.00
17	E1	70.2	92,550	1,239,534.00	11,106.00
18	B	11.1	119,004	1,961,680.40	14,280.42
19	D	14.7	157,331	4,551,888.50	18,879.72
20	E8	62.9	43,210	713,691.00	2,160.50

The highest score is achieved by A1 oil field. This indicates the suitability of A1 oilfield for CO_2 EOR and sequestration on the basis of intrinsic reservoir characteristics and with considering either the incremental oil production or the CO_2 storage capacity of the reservoir. The advantages of choosing this oil field include:

- Proximity to CO_2 source (SNG plant), 13.8 km, which will enable ease of transport and reduction in transportation cost.
- High oil saturation makes EOR operations profitable (Taber *et al*., 1977).
- With its current storage capacity, more than 18 $MtCO_2$, A1 oil field will be able to store the CO_2 produced from SNG plant (4.5 $MtCO_2$/year) for 4 years.
- Additional recovery of more than 45 MMSTB.

Unfortunately, field A1 does not achieve the miscibility whilst the key in a successful EOR operation is to achieve maximum contact between the oil and the CO_2 (Hester and Harrison, 2010). This is done by injecting the CO_2 into the reservoir so that the CO_2 is at miscible or near-miscible ("sub-miscible") pressure with respect to the oil. However, both the largest additional recovery and storage capacity is A1 oil field.

Oil field F is ranked second. Its score on CO_2 EOR and CO_2 sequestration suitability is almost close to oil field A1 and has the thickest seal for any oil field providing more secure geological containment. This field comprises satellite fields hencefor scoring purposes these clustered into one field. The third, fourth, and fifth ranked oil fields are E, D6, and D3 respectively. E Oil field is relatively has less favourable criteria for CO_2 sequestration due to having thin seal (Jerry and Stefan, 2002). Nevertheless, detailed assessment is needed to evaluate the seal potential that includes seal geometry, seal capacity and seal integrity.

D6 is the only oil field that has a willing partner at the present timein which the operator planned to apply CO_2 EOR in this field. The highest injectivity is owned by oil field D3. Higher injectivity reflects the ability to handle high injection rate of CO_2 and the less number of wells required (CO_2CRC, 2008). This would be a special advantage for D3 oil field to be able to handle high rate of CO_2 produced from SNG plant.

Oil field D is ranked nineteenth due to low capacity for CO_2 sequestration and less oil can be recovered from EOR. As a result, it may be uneconomic, or the cost of bringing CO_2 to it from source may be prohibitively high. However, this field may move up in ranking if the field is becoming more depleted since storageis a passive by-product and is equivalent to all the CO_2 that remains in the field after oil production, by trapping processes, such as residual gas and buoyancy trapping.

The score range among the oil fields is relatively close because several criteria have been assumed. For instance, number of abandoned well and contamination of other resources criteria are assumed due to inadequate data availability. It is assumed that existing abandoned wells are well plugged and appropriately abandoned. 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 and the likelihood to contaminate other resources is small (ADB and LEMIGAS, 2012; CO_2CRC, 2008).

B. Source-sink Matching

There are three major oil field clusters located in the north, southeast and west. Figure 2 shows the geographical distribution of the clustered oil fields with the SNG Plant as the centre point, shown by star. This approach implies that a cluster can be considered as a kind of 'super field' consisting of multiple fields with a main trunk pipelines pass through within these fields. A cluster of oil fields, by nature, will consist of fields of variable size and injectivity (TNO, 2008). Fields that exclude in clusters are considered too remote for practical tie-in into trunk pipelines as a result have less economic benefits and are not favorable for CO_2 EOR and sequestration at the present time (Massachusetts Institute of Technology, 2009; Peter, 2010). Many of these fields have small reservoirs that are uneconomic from an incremental oil recovered and storage perspective.

The development of trunk pipelines networks will be prioritized crossing the main clusters and based on stepwise realization (Figure 2). In the first step, pipeline is constructed to west cluster then extended to the southeast clusterand finally the pipeline is extended to the north cluster. West cluster is selected for early development because this cluster has the highest ranking of oil field and has oil field (D6) that willing to develop CO_2 EOR. Proximity to the source is also another consideration. Early pipelines development would likely not require extensive construction since there is potential to reuse the existing pipelines. Reusing this infrastructure can offer big economic benefits, given that the installations are timely available. Redevelopment from scratch is cost-ineffective and technically complicated (use it or lose it) (DHV, 2009). However, these pipelines have not been designed for high pressure CO_2 delivery. Detailed pipeline design studies on the reuse of former pipelines may point at certain technical or cost barriers. If the opportunity to reuse the existing pipeline is not possible, dedicated pipelines might be required and there is possibility grants the access the Right of Way (RoW).

If this first step successful then it would be step stones and lesson learned towards further extension to the southeast cluster. Interfield pipelines will connect the adjacent fields as much as possible to transport the CO_2 to the various wellsand eventuallyties in into the trunk pipeline.

Cluster system provides a semi regional demand analysis of CO_2 required to store or use for EOR purpose as depicted in Figure 2. The largest CO_2 demand is in southeast cluster, accounted for around 27 $MtCO_2$ storage capacity. This cluster has also the most promising recoverable oil with almost 150 MMstb. If the whole clusters are combined, they can handle 72 $MtCO_2$ for over 13 years. However, here we are looking at sink that would capable of storing of CO_2 for more than 20 years. In the meanwhile the

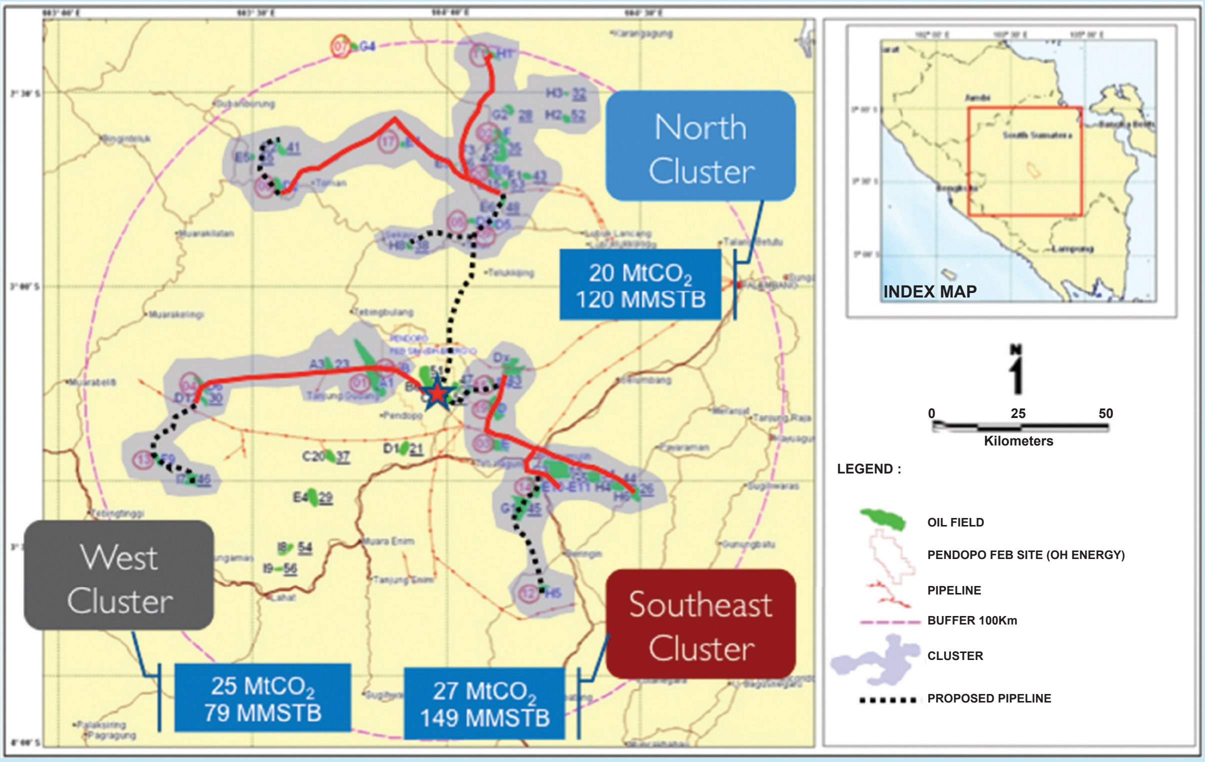

Figure 2
Clusters, Pipeline Network Development and Storage Capacity

source would typically deliver 4.5 Mt CO_2 per year over an expected life cycle of some 20 years. From the portfolio of sinks it is clear that no single oil field or cluster is capable to accommodate a constant yearly injection rate of 4.5Mt/yr over decades.

C. CO_2 Injection Profile for CO_2 EOR

The results of CO_2 injection profile for CO_2 EOR can be seen in Figure 3, Figure 4 and Figure 5 for north, west and southeast clusters, respectively. The profile in each clusters describes the demand of CO_2 required to recover oil in which the incremental is determined by the miscibility. To illustrate this, Field A1 is categorized as immiscible CO_2 flood with potential incremental recovery around 45 MMBbl (5% from OOIP). As a consequence the amount of CO_2 needed to recover 45 MMBbl is 6.8 $MtCO_2$ which is derived from the base case. Although in EOR operation the injected CO_2 is not entirely lost due to trapping mechanism occurred in the reservoir in this case, however, the recycled CO_2 is not simulated. The main reason is at the scale of this study, it would be a daunting task to simulate a considerable amount of CO_2. Nevertheless, it can be assumed 50% of CO_2 trapped at the end of the injection period.

The regional injection for three clusters is shown in Figure 6. The CO_2 injection profiles as presented in three clusters are to be considered as high cases in terms of volumes. Some scenarios were made for each cluster which differentiate the CO_2 coming "on stream" into the pipelines. On stream phase describes the availability of the infrastructures and the readiness of the pipelines to transport the CO_2 to the oil fields for EOR purposes (DHV, 2009; Babadagli, 2006). As an illustration, North cluster has several on stream phases which dictate the timing of injection to begin and stop. D5 and D3 oil fields will be on stream in the first year followed by E8, F and H1 in the second phase-two years after injection begin at the first phase. Eventually, this cluster will cease injecting CO_2 after the third phase comes on stream at the fourth year for 10 years. Table 4 summarizes the on stream phase for three clusters.

The transition periods between each phase and the magnitude of injection rate determine the profile of the CO_2 injection. Short transition period results accelerated injection profile while injection rate affects on slope of the profile (DHV, 2009). The number of high rank oil fields contained in the cluster contributes the decline of the curve. A more accelerated profile may indicate the oil fields to become operational in a very fast sequence whereas a slower profile reflects the less number of oil fields in the cluster that have suitability of for CO_2 EOR and sequestration instead of make full use of the available oil fields.

Clearly that operational and economical factor will eventually decide which profile will be favourable for a particular cluster (Massachusetts Institute of Technology, 2009; DOE, 2008). ”Carbon Management GIS: CO_2 Injection Cost Modeling. It may be conjectured, that the larger fields/clusters will be kept at a ‘slow’ profile, accommodating the larger part of the base load CO_2 supply, and that the smaller fields would benefit from a more accelerated profile, superimposed on that of the larger fields as infill (DHV, 2009).

This scenario illustrates that several top rank oil fields alone in each cluster are unable to accommodate 4.5 million ton CO_2 supply from the SNG plant in the perspective of greenhouse gas mitigation. It may take the whole fields in cluster to absorb the excess of CO_2. However, this scenario provides a demand analysis of the CO_2 requiredin each cluster to be purchased by oil companies and a schedule for CO_2 injection.

D. CO_2 Injection Profile for CO_2 Sequestration

The injection profile for CO_2 sequestration is shown in Figure 7 indicating a baseline CO_2 supply rate (4.5 Mt/yr) – purple line, has to be accommodate by fields in cluster. Each field has distinct filling rate corresponding to the reservoir characteristics. Therefore, in order to accommodate the supply rate, field’s management is required by activating new fields nearby or in another cluster of which the schedule is shownin Figure 7. Storage capacity

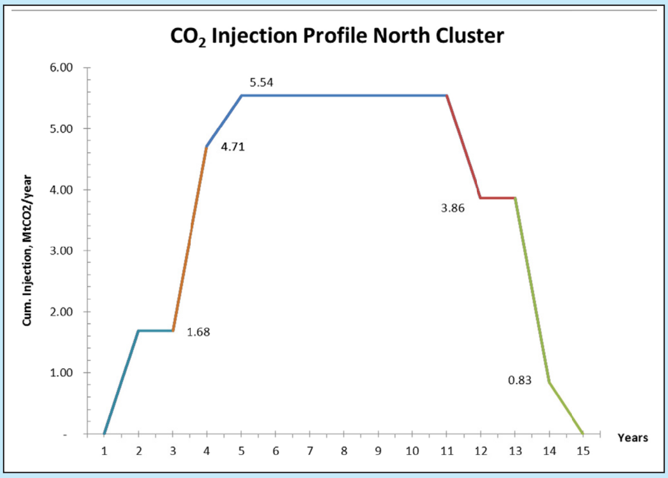

Figure 3
CO_2 injection Profile in the North Cluster

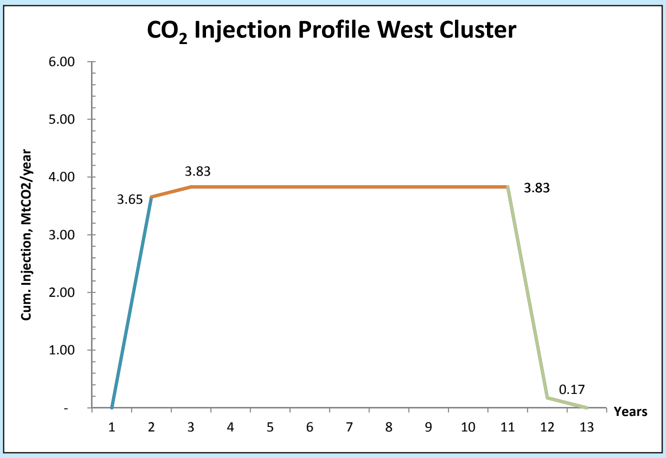

Figure 4
CO_2 injection Profile in the West Cluster

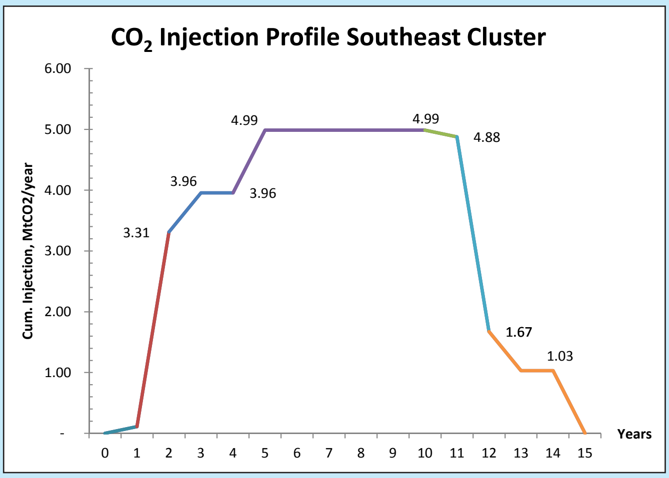

Figure 5
CO_2 injection Profile in the Southeast Cluster

Table 4
Summary on Stream Phase for All Clusters

Cluster	On stream Phase	Field's Rank	Fields Code	Cum. Injection per Phase		Period	Injection Start
				ton/day	Mton/year	year	i year
NORTH	1	9	D5	4,614.90	1.68	10	1
		5	D3			10	
	2	20	E8	8,283.02	3.02	10	3
		2	F			10	
		11	H1			10	
	3	17	E1	2,287.64	0.83	10	4
		8	D2			10	
WEST	1	18	B	10,013.15	3.65	10	1
		1	A1			10	
		4	D6			10	
	2	13	F9	475.16	0.17	10	2
SOUTHEAST	1	15	D4	303.53	0.11	10	1
	2	19	D	8,773.28	3.20	10	2
		3	E			10	
	3	14	E10	1,760.54	0.64	10	3
	4	12	H5	2,825.93	1.03	10	5

in another cluster is expected to be released soon if fields in the cluster unable to handle. As a consequence, storage fields will have to become operational in a very fast sequence.

Fields considered have capability of handling high rate and large storage capacity should be combined with fields (colored lines) that do not have this features. As indicated on blue line, entire CO_2 supply is able to be absorbed during injection 13 year period. In fact, it has some surplus of storage capacity.

In the scenario assumed above, the cluster of storage fields would be filled at a constant rate of hundred percent over certainperiods depends on the capacity of the field. This approach does not assume that a cluster becomes available only after another cluster has ceased the injection and connected to a trunk line. However, it implies the availability of storage capacity may be postponed.Make full use of the available injection capacity in the satellite fields can help absorbing the supply.

Another strategy, the storage operator might choose to run all the cluster fields in parallel

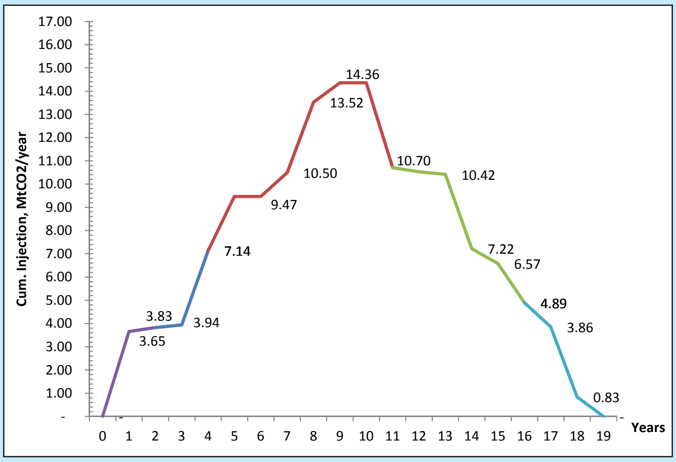

Figure 6
Regional CO_2 Injection Profile

throughout the contract duration (DHV, 2009). The drawback of this mode of operation is, that all assets should be kept operational throughout, which is not cost effective. At the other extreme, the operator may choose to run the fields in a purely sequential mode, activating a new field within the cluster only when the first field comes off a ‘plateau’ like injection profile into decline. As discussed in section 1.6, no single depleted oil field at within 100 km from SNG Plant is capable of handling theoutput of one large point source. Therefore, there will always be the need to run some fields in parallel.

Notwithstanding that this analysis provides insight for determining the most efficient injection strategy of CO_2, however, the thermodynamic and/or mechanical constraints (reservoir properties) on the CO_2 injection (Manrique, 2007) and have to be studied in detail in the overall strategy and management of the cluster injection process.

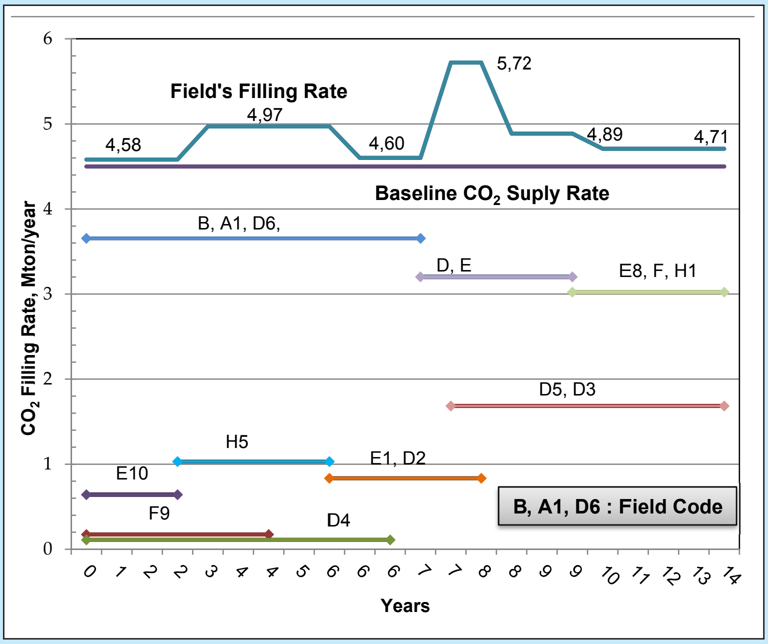

Figure 7
Schedule and CO_2 Injection Profile for CO_2 Sequestration

IV. CONCLUSIONS

- The A1 oil field has the highest rank in the sink scoring indicating that this field has highest suitability for CO_2 EOR application and CO_2 storage. F Oil field is a close second in ranking which has good containment and followed by E oil field at third. Although D6 oil field ranked in fourth but it is the only field that has willing partner for CO_2 EOR application. Both for the highest additional recovery potential and storage capacity is A1 oil field.
- Three clusters are formed, north, southeast and west cluster to establish pipelines network development. A cluster contains a few core fields (20 highest rank), that in combination with lower suitability oil fields can carry the larger part of the required constant CO_2 supply and injection and capacity over several years.
- West cluster is selected for early pipelines development due toproximity to the source, having the most suitable field for CO_2 EOR and sequestration, willing partner to implement CO_2 EOR and less extensive infrastructure development at the early stage.
- The largest CO_2 storage potential is in southeast cluster, 27 $MtCO_2$. Total storage capacity for the whole clusters is 72$MtCO_2$ or equal to13 years storage capacity with 4.5 $MtCO_2$/yr filling rate. While total storage capacity for all oil fields identified within 100 km radius is more than 92 $MtCO_2$ or 20 years filling period.
- Injection profile for CO_2 EOR in each cluster responded differently correspond to field's characteristics (injection rate), on stream phase and the number of suitable fields for CO_2 EOR.
- By combining different field characteristics (injectivity and storage capacity), the injection strategy developed is successful to manage CO_2 supply from SNG Plant. Besides providing the CO_2 injection profile for storing CO_2, the profile supplies also the schedule and strategy needed to activate new field.

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