CO_2 STORAGE CAPACITY ESTIMATION OF DEPLETED OIL AND GAS RESERVOIRS IN INDONESIA

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ABSTRACT

Implementation of CO_2 capture and geological storage technology at the scale needed to achieve a significant and meaningful reduction in CO_2 emissions requires knowledge of the available CO_2 storage capacity. Various geological formations located across many islands in Indonesia appear to be potential to store the anthropogenic CO_2, particularly in depleted oil and gas reservoir. These depleted oil and gas reservoirs are appropriate candidates for CO_2 storage. However, the capacity of this geological formation has not been estimated yet. The objective of this study is to estimate the storage capacity of depleted oil and gas reservoirs in Indonesia using the methodology, developed by Carbon Sequestration Leadership Forum (CSLF). Screening result from our databases showed there were 103 depleted oil and gas fields were considered depleted from their Np/Ult ratio (hydrocarbon cumulative production over ultimate recovery) which were $\geq$ 55%. However, only 48 fields had complete data to estimate. We used the methodology that was initially developed by CSLF but then it had been simplified by Poulsen et al. We considered this methodology as the most convenient to use in this country scale of assessment despite of any simplification had been made. Estimation result showed Riau and South Sumatra region have large storage capacities which are around 229 and 144 $MtCO_2$ respectively. The estimates of CO_2 storage capacity reflects the actual capacity that was based on data availability during the assessment. The potential storage capacity might change as data becoming more available. Hence, the storage capacity map resulted from this study is not conclusive estimation. However, this study indicates that Indonesia has huge potential of CO_2 storage in depleted oil and gas reservoirs.

Keywords: *storage capacity, storage efficiency factor, depleted oil and gas reservoirs*

I. INTRODUCTION

Three approaches can be taken to mitigating anthropogenic CO_2 emissions to the atmosphere in response to climate change: 1) increasing energy efficiency and conservation, 2) switching to less carbon-intensive fuels or to renewables, solar and nuclear energy, and 3) artificially increasing the capacity and capture rate of CO_2 sinks (Bachu, 2003). The latter could be achieved through the capture of CO_2 from large stationary sources prior to potential release into the atmosphere, and storage in various geological formations. This process is known as Carbon Capture and Storage, or CCS. Implementation of CO_2 capture and geological storage technology at the scale needed to achieve a significant and meaningful reduction in CO_2 emissions requires knowledge of the available CO_2 storage capacity.

Various geological formations located across many islands in Indonesia appear to be potential to store the anthropogenic CO_2, particularly for depleted oil and gas reservoir. After more than a century of intensive petroleum exploitation, thousands of oil and gas fields in Indonesia are approaching the ends of their economically primary stage. The future storage capacity will increase in time as more fields are depleted. These depleted oil and gas reservoirs are prime candidates for CO_2 storage. However, the capacity of this geological formation has not been estimated yet before.

The objective of this study is to estimate the storage capacity of depleted oil and gas reservoirs in Indonesia using the methodology developed by CSLF. The type of the estimation and its position of storage capacity are also described in Techno-Economic Resource-Reserve Pyramid for CO_2 Storage Capacity in order to provide clear certainty of the estimated capacity and its constraint.

II. CO_2 STORAGE CAPACITY AND ITS CLASSIFICATION

CO_2 storage capacity is defined as an estimate of the amount of CO_2 that can be stored in subsurface geologic formations. Exact quantification of storage capacity is not possible due to uncertainties inherent to subsurface evaluation. Therefore storage capacity is always at best an approximation of the amount of CO_2 that can be stored and it also relies on the integrity, skill and judgment of the evaluator and is affected by the geological complexity, stage of exploration or development, amount of existing storage and of available data.

Factors affecting CO_2 storage capacity include the density of the CO_2 at subsurface reservoir conditions, the amount of interconnected pore volume of the reservoir rock and the nature of the formation fluids. Due to the flow behaviour of CO_2 in the subsurface, not all potentially available pore volume of the reservoir will become occupied during injection and migration, with flow preferentially occurring either upward due to buoyancy forces or laterally below low permeability zones (i.e. spreading out in thin layers beneath intraformational seals or the regional top seal rather than filling the entire pore volume). This can make CO_2 storage capacity volumes difficult to calculate, particularly in the reservoir rocks underlying defined structural or stratigraphic closures, where much of the available rock pore volume can be bypassed by CO_2 preferentially utilising higher permeability zones (Gibson-Poole, 2008).

The potential CO_2 storage capacity should therefore be assessed in terms of available interconnected pore space, accounting for factors such as injection rate, rate of CO_2 migration, the dip of the reservoir, the heterogeneity of the reservoir and the potential for fill-to-spill structural closures encountered along the migration path. In addition, long-term prospects for storage, including residual trapping, dissolution into the formation water or mineral trapping (formation of new minerals) can also be considered (especially for estimating potential storage volume within deep saline formations) (Gibson-Poole, 2008). Such issues are best addressed by building geological models and running numerical flow simulations. However, in this study various trapping mechanisms affecting storage capacity are not considered since it requires extensive data and works.

Classifying storage capacity is needed to provide consistent and accepted methodologies and can be compared with other estimates conducted in another country. Currently, there are two major works providing methodologies for the estimation of storage capacity of CO_2 in geological formations. These are: 1) the DOE (2006) ‘Methodology for Development of Carbon Sequestration Capacity Estimates’ prepared for the Carbon Sequestration Program of the National Energy Technology Laboratory, U.S. Department of Energy (DOE), by the Capacity and Fairways Subgroup of the Geologic Working Group of the DOE Regional Carbon Sequestration Program in December, 2006, 2) the CSLF (2007) ‘Estimation of CO2 Storage Capacity in Geological Media – Phase II’ prepared by the Task Force on CO_2 Storage Capacity Estimation for the Technical Group (TG) of the CSLF in April, 2007.

In this study, we used CO_2CRC Storage Capacity Classification, because it has not only incorporated the resource pyramid from CSLF (2007)-Figure 1, but also adapted it and took into account of the SPE Petroleum Resources Management System for the classification of petroleum resources and reserves (SPE, 2007). Combination of these concepts provides comprehensive coverage with respect to the use of pore volume. It merges point of view from established petroleum industry and new concept of CO_2 storage.

III. STORAGE CAPACITY ESTIMATION METHODOLOGY

This study estimate of CO_2 storage volume was conducted on identified depleted oil and gas fields in Indonesia. Oil and gas fields comprised certain number of reservoirs, estimating CO_2 storage capacity in the scale of field is made possible by summing the individual reservoirs. Unlike coal seams and saline formations, oil and gas fields are considered as a single discrete, thus capacity for CO_2 storage in hydrocarbon reservoirs in any particular region at any scale is given by the sum of the capacities of all reservoirs in that area.

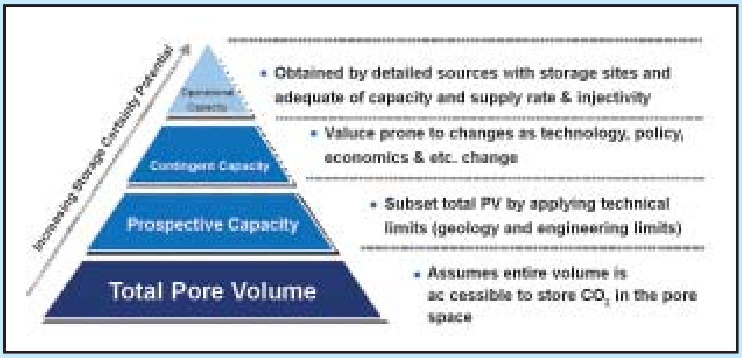

Figure 1
Techno-Economic Resource-Reserve Pyramid for CO_2 Storage Capacity (modified from CO2CRC, 2008)

We used the methodology for estimating storage capacity in depleted oil and gas reservoirs that initially developed by CSLF but then simplified by Poulsen *et al.* CSLF methodology provides some formulas for depleted oil reservoirs, depleted gas reservoirs and both depleted oil and gas reservoirs. Those formulas assume that volume previously occupied by the produced hydrocarbons becomes, by and large, available for CO_2 storage. It also represents the scale of calculation which is theoretical storage capacity or maximum upper limit to a capacity estimate, and its position in the resource pyramid occupies the whole of the resource pyramid. The following equation is the original equation for depleted oil reservoir (1) and depleted gas reservoir (2) from CSLF:

$$MCO_2t = \rho CO_2r \times [\, R_f \times OOIP / B_f - V_{iw} + V_{pw} \,] \quad ....\ (1)$$

$$MCO_2t = \rho CO_2r \times R_f \times (1 - F_{IG}) \times OGIP \times [(P_s \times Z_r \times T_r) / (P_r \times Z_s \times T_s)]\ . \quad ....\ (2)$$

CSLF provides also alternative equation (3) that combines both equation for estimating storage capacity in depleted oil and gas reservoir:

$$MCO_2t = \rho CO_2r \times [R_f \times A \times h \times \varphi \times (1 - S\,w) - V_{iw} + V_{pw}] \quad ....\ (3)$$

where:

F_{IG} : the fraction of injected gas
P, T, Z : pressure, temperature and the gas compress ibility factor
R_f : recovery factor
B_f : the formation volume factor that brings the oil volume from standard conditions to in-situ conditions
V_{iw} : volumes of injected water (applicable in the case of oil reservoirs)
V_{pw} : volumes of produced water (applicable in the case of oil reservoirs)
A, h, φ : reservoir area, thickness, and porosity
S_w : water saturation
OOIP : original oil in place
OGIP : original gas in place

Above equations incorporated recovery factor, OOIP and OGIP in which these constitute key components in reserves databases. It also reflects the approach that is taken based on production of the hydrocarbon and converting them to the in-situ condition by multiplying with formation volume factor.

Poulsen *et al.* (2009) in his report Geological Assessment for CO_2 Storage in the Bohai Basin, East China, simplified the formula made by CLSF. In his work, basically Poulsen eliminates some variables by not taking into account fraction of injected gas, volumes of injected and produced water. This assumes that the reservoir is not flooded during secondary and tertiary oil recovery (pressure-depleted fields). It is understandable since if we are going to use the equation no.3 in country or state scale assessment, it will require extensive data which are too early in the coarsest scale of assessment. He also makes some modification with respect to the equation by adding storage efficiency factor. Following is simplified equation that proposed by Poulsen *et al.*:

$$MCO_2 = \rho_{CO_2 r} \times UR \times Seff \quad .....\ (4)$$

where:

ρCO_2r : CO_2 density at reservoir conditions (best estimate)

URp : proven ultimate recoverable oil or gas
Seff : storage efficiency factor

URp represents Rf × OGIP and Rf × OOIP respectively of the CSLF equations.

Basically the above equations used production based approach where records of produced volumes of hydrocarbon are available. CO_2CRC reported when such data are available, it is possible to apply efficiency to production data to convert it to CO_2 storage volumes. Alternative simple approach is replacing produced hydrocarbons by CO_2 on a volume-for-volume basis (at reservoir pressure and temperature). CO_2CRC and US DOE proposed also alternative approach which is based on volumetrics. This approach uses standard industry methods to calculate original oil in place (OOIP) or original gas in place (OGIP). OOIP is calculated by multiplying formation area (A), net oil column height (h_n), average effective porosity (φ_e), and oil saturation (1 - water saturation as a fraction [Sw]). Below is the formula (5) proposed by US DOE:

$$G = A\ h\ \varphi\ (1-S\ )B\ \rho\ E \qquad ..... (5)$$

Another fundamental assumption made on the equations developed by CSLF is that the reservoirs are not in hydrodynamic contact with an underlying aquifer. If we do not consider this assumption on the reservoirs that have contact with aquifer mean reducing in storage capacity is occurred due to invading of formation water as the pressure declines because of production. However, it is worth to note by using these equations we should be aware that there will be offset of the actual storage capacity due to:

- Imperfect inversion of processes that occurred during production (e.g. replacement of produced oil or gas by water-CO_2 may not completely replace this imbibed water).
- Production of gas by solution gas drive. Solution gas should not be considered in storage capacity calculations because it is implicitly taken into account in oil reservoirs through the oil shrinkage factor.
- Waterflooding.
- Capillarity, viscous fingering and gravity effects (Stevens *et al.*, 2001).
- Pressure perturbations of the formation during production (for example, compromise to the seal by well penetration or by deformation during production.
- The seal will respond in the same manner to trapped CO_2 as to the oil and gas originally in place. Thus the pressure cannot be brought back to the initial reservoir pressure and the capacity would be lower.

In contrast, this formula has also the potential to increase the storage capacity because of failure to take into account some considerations such as:

- Reservoir might behave elastically during pressure depletion and subsequent re-pressurisation, such that the reservoir stress path is reversible. Hence, CO_2 can be injected until the reservoir pressure is brought back to the original, or virgin, reservoir pressure. While in other cases the pressure can be raised beyond the original reservoir pressure as long as it remains safely below the lesser of the capillary entry pressure and the threshold rock-fracturing pressure of the seal (caprock), in which case the CO_2 storage capacity would be higher due to CO_2 compression (CSLF, 2007).
- Dissolution of CO_2 into residual and associated water.
- Mineral trapping.
- Miscibility of CO_2 into oil.

However, the consideration of the method used for this study was selected based on available data which is reserves databases.

IV. STORAGE EFFICIENCY FACTOR

A storage efficiency factor (E) where applied to above formulas reflects the volume accessible to injected CO_2 or a fraction of the total pore volume that is filled by CO_2. It also adjusts total gross thickness to net gross thickness, total area to net area and total porosity to effective (interconnected) porosity actually containing CO_2. Moreover, storage efficiency presents the fraction of CO_2 that contributes in trapping mechanisms such as dissolution of CO_2 in situ into oil or water. E can be derived from local experience or reservoir simulation.

The two methods above, either volumetric or production based, have storage efficiency factor built into their respective formulas. Unlike CO_2CRC, US DOE and Poulsen *et al.*, CSLF does not incorporate the storage efficiency factor explicitly in the equation, but separate it from the main equation. Without E, CSLF equations present the Total Pore Volume or maximum upper limit to capacity. Inclusion of E provides a means of estimating storage volume for a basin or region with the level of knowledge (uncertainty) in specific parameters determining the type of CO_2 storage capacity estimated. CSLF reported there were three other factors control the effectiveness of the CO_2 storage process: CO_2 mobility with respect to oil and water; the density contrast between CO_2 and reservoir oil and water, which leads to gravity segregation; and reservoir heterogeneity. All these processes and reservoir characteristics that reduce the actual volume available for CO_2 storage can be expressed by capacity coefficients ($C < 1$) in the form In other words this could be decipherable as storage efficiency factor. Following is capacity coefficient proposed by CSLF:

$$Mco_2e = C_m \times Cb \times Ch \times C_w \times C_a \times Mco_2t \equiv C_e \times Mco_2t \quad \text{.......} (6)$$

where MCO_2e is the effective reservoir capacity for CO_2 storage or in the CO_2CRC methodology it is mentioned as prospective capacity, the subscripts *m*, *b*, *h*, *w* and *a* stand for mobility, buoyancy, heterogeneity, water saturation, and aquifer strength, respectively, and refer to the phenomena discussed previously, and the coefficient C_e is a single effective capacity coefficient that incorporates the cumulative effects of all the other. It should be noted since equations (1), (2), and (3) are intended for theoretical storage capacity hence the storage efficiency in these equations is implied as 1. On the other hand, the above capacity equation is for effective/prospective storage capacity. The equation we used in this study derived and modified by Poulsen *et al*. from CSLF which is proposed 1 as the value storage efficiency factor and it is in line with the assumptions that were made and the scale of assessment. Up to now no range of CO_2 storage values is proposed for oil and gas fields, indicating a relatively good understanding of volumetrics of these systems.

V. CO_2 DENSITY

CO_2 storage is generally expected to take place at depths below 800m, where the ambient pressures and temperatures will result in CO_2 being in a liquid or supercritical state. This supercritical state (temperature = 31.1°C and pressure = 72.9 atm) yields rather uncommon properties. It can adopt properties midway between a gas and a liquid. Under these conditions, the density of CO_2 will range from 50 to 80% of the density of water. Being in dense form, CO_2 storage in geological formations provides the potential for efficient utilisation of underground storage space in the pores of sedimentary rocks.

Therefore estimating storage capacity where the density of CO_2 in supercritical state is required in order to result best approximation. To generate reliable thermodynamic data of carbon dioxide under this condition require equation of state (EOS) that can accommodate high pressure and temperature condition. However, so far knowledge of the thermodynamic properties of carbon dioxide remained unsatisfactory. Thus, since 1973, numerous experiments including state-of-the-art experiments with significantly improved accuracy have been performed in order to improve the quality of the entire data set (Wagner, 1995). Then Span and Wagner (1995) developed new correlation of carbon dioxide properties and presented a new equation of state for carbon dioxide explicit in the Helmholtz energy, which is designed to overcome the disadvantages of the existing correlations and cover properties in the critical region. Therefore, we used Span and Wagner EOS to generate reliable CO_2 density in supercritical state.

VI. RESULTS AND DISCUSSION

We defined depleted oil and gas fields which have Np/Ult ratio (hydrocarbon cummulative production over ultimate recovery) more than or equal $\geq$ 55%. Screening result from our databases showed there were 142 depleted oil and gas fields. However, only 66 from 142 fields had complete data to be estimated. Data availability is big challenge in estimating CO_2 storage capacity in such scale of assessment.

Figure 2 shws the result of storage capacity estimation from depleted oil and gas fields in Indonesia by using the methodology that developed by Poulsen *et al.*

This initial estimates show Riau and South Sumatra are considered to have large storage capacities which are around 229 and 144 million tonne of CO_2 respectively. This is not apart from the fact that many oil and gas fields were discovered in these regions and hydrocarbon extraction has been going on since a century ago. Moreover, Riau region is located in extensive Central Sumatra Basins and South

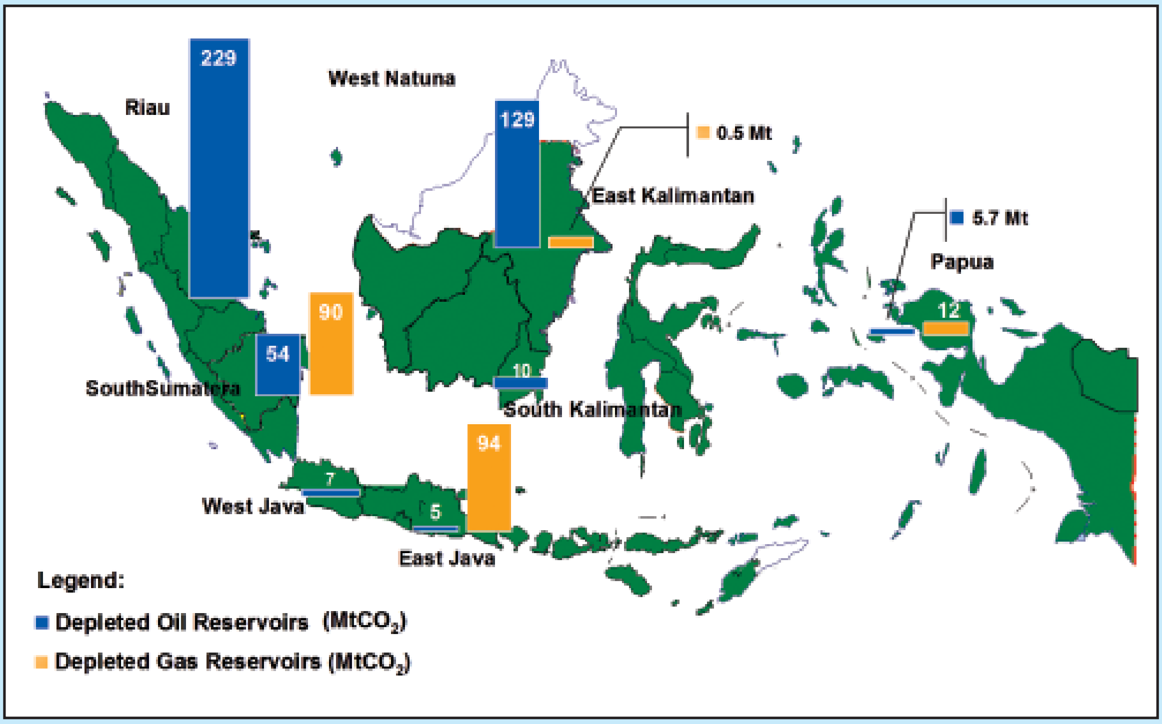

Figure 2
Map of storage capacity distribution of depleted oil and gas reservoirs in Indonesia based on data available in 2009

Sumatra region has basin that extends to the north of Lampung region. Extensive petroleum activities in East Kalimantan have provided potential depleted hydrocarbon reservoirs in where this region has CO$_2$ storage capacity almost 130 MtCO$_2$. In the meanwhile, storage capacity in Java Island is circa 105 MtCO$_2$ in total.

The distribution of CO$_2$ storage capacity map above reflects theoretical maximum storage capacity that was based on data availability during the assessment. The potential storage capacity might increase as data more available. This is also coupled with Van der Meer reported that the general quality of the data used for a given case affects the reliability of the outcome of the individual calculation. He proposed a system for rating data quality. Moreover, the total set of data that is used in the capacity calculation should be rated: from representative, based on deterministic measurements and reliable, to based on guestimation and with maximum uncertainty. All estimated CO$_2$ storage capacity data must be assigned one of these proposed classifications, which should be arrived at according to common sense and based on sound engineering judgment.

Thus, the map resulted from this study is not a conclusive estimation. Type of estimation that we conducted is theoretical storage capacity which is located at the bottom of Techno-Economic Resource-Reserve Pyramid for CO$_2$ Storage Capacity. At this type, degree of geological and economic uncertainty associated with a capacity estimate is still high. In order to achieve operational capacity, the best-known and highest quality capacity, which is placed at the apex of the pyramid, requires a lot of data and effort and the focus of assessment will be very site specific. However, from this estimation, Indonesia has huge potential of CO$_2$ storage in depleted oil and gas reservoirs.

VII. CONCLUSIONS

- The methodology used for estimating storage capacity in depleted oil and gas reservoirs that simplified by Poulsen *et al.* from CSLF methodology presents convenient means in estimating storage capacity at country scale.

- 1 (one) was chosen as storage efficiency factor in which it is in line with the basis of assumption that was made in the formula.
- Storage capacity classification proposed by CO_2CRC provides comprehensive coverage with respect to the use of pore volume. It merges point of view from established petroleum industry and new concept of CO_2 storage.
- Reliable CO_2 density calculation plays important role to generate best approximation of storage capacity and EOS that was developed by Span and Wagner, (1996) can provide this.
- The estimates showed depleted oil and gas fields in Indonesia have enormous potential for CO_2 storage. At the moment, the largest storage capacity located in Riau region and followed by South Sumatra with capacity 229 and 144 million tonne of CO_2 respectively.
- The storage capacity resulted from this study is not a conclusive estimation. The potential storage capacity might increase as more data are available and potentially change current rank of largest storage capacity in each region.

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