

A comparative study of US DOE, CSLF, and poulsen volumetric methods for CO₂ storage capacity estimation

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ABSTRACT

This study aims to estimate the theoretical carbon dioxide (CO₂) storage capacity of the T Formation using the US DOE, CSLF, and Poulsen methods. The calculation begins by determining the CO₂ density at reservoir conditions utilizing the real gas approach (Standing-Katz), which subsequently serves as a primary parameter for all three methods. The results show that the estimated CO₂ storage capacities using the US DOE, CSLF, and Poulsen methods are 12.92 Mt, 12.06 Mt, and 14.51 Mt, respectively. This variance is driven by differing methodologies: the US DOE and CSLF methods apply a volumetric approach based on reservoir geological parameters, whereas the Poulsen method relies on a production data-driven approach.



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INTRODUCTION

Global climate change caused by rising greenhouse gas emissions, particularly CO₂, has become a major issue garnering international attention (International Energy Agency, 2021). As part of the commitment to mitigate global warming, the upstream oil and gas industry has begun transitioning toward eco-friendly technologies, including Carbon Capture and Storage (CCS), a technology that captures CO₂ emissions from industrial sources, then injects and permanently stores them in subsurface geological formations (Metz et al., 2005).

Depleted oil and gas reservoirs are highly potential candidates for CO₂ storage due to the availability of relatively comprehensive subsurface data and their proven ability to trap hydrocarbon fluids over geological timescales (Heidug, 2013). A crucial initial step in implementing a CCS project is estimating the theoretical storage capacity to assess the technical potential and preliminary feasibility of a reservoir. Several commonly used volumetric methods include the US DOE (Goodman et al., 2011), CSLF (Bachu, 2008), and Poulsen (Poulsen et al., 2011) methods. These three methods employ different approaches, assumptions, and calculation parameters, which can lead to varying capacity estimates even when applied to the exact same reservoir.

Previous studies comparing the CSLF and US DOE methodologies have demonstrated that hydrocarbon production data is a vital component in estimating storage capacity within depleted reservoirs (Bachu, 2008). Other research indicates that production-based methods (Poulsen) tend to yield larger capacity values compared to static volumetric methods (Poulsen et al., 2011). Focusing on the T Formation within the Asri Basin, prior geomechanical studies (Ridhandi et al., n.d.; Lathifah et al., n.d.) evaluated pore pressure, fracture pressure, and seal integrity, but stopped short of quantitatively calculating the CO₂ storage capacity using internationally standardized volumetric methods. Consequently, a research gap remains regarding the integration of geomechanical analysis with CO₂ storage capacity estimations using multiple simultaneous calculation methods on the T Formation.

This study aims to analyze the discrepancies in CO₂ storage capacity estimates for the T Formation using the US DOE, CSLF, and Poulsen methods.

RESEARCH METHODS

1. Research Design: This study employs a quantitative-comparative approach, comparing the CO₂ storage capacity calculation results from three volumetric methods (US DOE, CSLF, and Poulsen) applied to identical reservoir data.
2. Research Subject and Object: The object of this research is a hydrocarbon reservoir in the T Formation, Widuri Field, Asri Basin (offshore Southeast Sumatra), managed by PT Pertamina EP OSES and predicted to reach a depleted state.
3. Data Collection Technique: Secondary data was sourced from PT Pertamina EP OSES, encompassing reservoir rock properties, reservoir fluid data, hydrocarbon production data, fluid injection records, thermodynamic conditions of CO₂, and other supporting calculation data.
4. Research Instruments: Calculations and data analysis were conducted using Microsoft Excel and Microsoft Word, supported by scientific literature including journals, books, technical reports, and official corporate documents.
5. Data Analysis Technique: The analysis was carried out through the following workflow: (1) identifying the problem regarding discrepancies between the volumetric methods; (2) processing data to obtain the actual CO₂ density at reservoir conditions using the real gas equation (Equations 1-3, with the compressibility factor derived from the Standing-Katz chart); (3) calculating CO₂ storage capacity using the US DOE (Eq. 5), CSLF (Eq. 6), and Poulsen (Eq. 9) formulas — intermediate Equations (4), (7), and (8) correspond to supporting unit-conversion and volume-correction steps within this workflow and are not reported separately; and (4) conducting a comparative analysis of the results.

The CO₂ density at reservoir conditions is calculated using the real gas equation:

$$\rho_{CO_2} = \frac{PM}{ZRT} \quad (1)$$

Where ρ_{CO_2} is the CO₂ density (kg/m³); P is the reservoir pressure (Pa); M is the molecular mass of CO₂ (44.01 kg/kmol); Z is the gas compressibility factor; R is the universal gas constant (8.3144 J/mol · K); and T is the reservoir temperature (K). Pseudo-reduced pressure and temperature are calculated via:

$$Pr = \frac{P}{P_c} \quad (2)$$

$$Tr = \frac{T}{T_c} \quad (3)$$

CO₂ capacity using the US DOE method:

$$MCO_2 = A \times h \times \phi \times (1 - S_w) \times B \times \rho_{CO_2} \times R_f \quad (5)$$

CO₂ storage capacity using the CSLF method:

$$MCO_2 = \rho_{CO_2} \times [R_f \times A \times h \times \phi \times (1 - S_w) - V_{iw} + V_{pw}] \quad (6)$$

CO₂ storage capacity using the Poulsen method:

$$MCO_2 = \rho_{CO_2} \times (UR_o + UR_g) \quad (9)$$

Where A is the reservoir area; h is the reservoir thickness; ϕ is the porosity; S_w is the water saturation; B is the formation volume factor; R_f is the recovery factor; V_{iw}/V_{pw} are the

injected/produced water volumes; and UR_o/UR_g are the oil/gas ultimate recoveries (A in m²; h in m; ϕ , Sw, and Rf as fractions; B in reservoir m³/standard m³; Viw, Vpw, URo, and URg in m³). The critical properties of CO₂ used to compute the pseudo-reduced pressure and temperature (Equations 2 and 3) are the standard literature values $P_c = 7.3773$ MPa and $T_c = 304.13$ K.

RESULTS AND DISCUSSION

In the initial phase of the study, the CO₂ density at reservoir conditions was calculated using the real gas equation. The pseudo-reduced pressure and temperature were calculated using Equations (2) and (3), yielding $P_r = 1.45$ and $T_r = 1.2$ after converting the reservoir temperature to 359.26 K. Based on the Standing-Katz chart, the gas compressibility factor was determined to be $Z = 0.66$. Following the conversion of pressure to Pascals (10,686,878 Pa), the CO₂ density was calculated using Equation (1), yielding $\rho_{CO_2} = 238.6$ kg/m³. In field units, the reservoir pressure and temperature used correspond to approximately 1,550 psia and 367 °F, respectively. This density value was subsequently utilized as a core parameter across all three storage capacity estimation methods. Note: the CO₂ density calculation in Equation (1) is dimensionally consistent only when M and R are expressed on the same molar basis (e.g., $M = 0.04401$ kg/mol paired with $R = 8.3144$ J/(mol·K), or equivalently $M = 44.01$ kg/kmol paired with $R = 8,314.4$ J/(kmol·K)); the value $M = 44.01$ kg/kmol stated earlier should therefore be read together with R on a matching kmol basis.

By substituting the compiled reservoir parameters into Equations (5), (6), and (9), the CO₂ storage capacities were determined. The US DOE method yielded an M_{CO_2} of 12,915,547,987.82 kg (12.92 Mt), the CSLF method yielded an M_{CO_2} of 12,056,904,190.69 kg (12.06 Mt), and the Poulsen method yielded an M_{CO_2} of 14,514,329,510.63 kg (14.51 Mt).

Table 1 Comparison of CO₂ Storage Capacity Calculation Results

No	Method	Capacity (Mt)
1	US DOE	12.92
2	CSLF	12.06
3	Poulsen	14.51

The calculation results and parameter comparisons presented in Table 1 highlight significant variations among the three methods despite utilizing the exact same baseline reservoir data. This noticeable variance reflects the level of optimism and conservatism inherent to each theoretical approach when estimating the rock volume accessible for structural CO₂ storage. These numerical discrepancies arise because each method applies distinct geological cut-offs and fluid saturation assumptions regarding the post-production effective pore space.

The fundamental reason the Poulsen method yields the highest estimate is its exclusive reliance on produced hydrocarbon volumes, independent of the surrounding fluid dynamics. This approach assumes an ideal scenario where every barrel of hydrocarbon fluid extracted from the source rock immediately yields a vacant space that can be 100% reoccupied by CO₂ sequestration, completely omitting micro-level storage efficiency limitations (Poulsen et al., 2011).

Conversely, the lowest estimation value seen in the CSLF method stems from its far more complex and realistic fluid-phase mass balance approach. The CSLF method explicitly discounts the net storage capacity due to formation water encroaching back into the vacant pore space during the production lifespan. Furthermore, CSLF accounts for capacity reductions caused by trapped residual gas and the inability of injected CO₂ gas to fully displace the remaining subsurface formation water (Bachu, 2008).

Meanwhile, the US DOE method occupies a moderate middle ground by bridging these two concepts. It utilizes a standard storage efficiency coefficient, known as the *E*-factor. This coefficient serves as a long-term geological correction factor that reduces the theoretical rock volume based on reservoir heterogeneity and permeability scales, bypassing the need to run detailed hydrodynamic water movement simulations as required by the CSLF method (Goodman et al., 2011).

CONCLUSION

Based on the analysis and calculations, the CO₂ storage capacity in depleted reservoirs is strongly dictated by the geological cut-off parameters and fluid dynamics assumptions unique to each method. The Poulsen method yields the highest estimate at 14.51 Mt due to its optimistic approach based on cumulative production volumes (ultimate recovery) without considering aquifer interactions. On the other hand, the CSLF method offers the lowest, most conservative outcome at 12.06 Mt because it integrates pore space reductions driven by water influx and residual gas trapping phenomena. The US DOE method provides a moderate estimation of 12.92 Mt by using a storage efficiency factor to account for macro-scale rock heterogeneity. Selecting the appropriate methodology is critical in carbon sequestration planning to prevent the overestimation of subsurface storage capacities.

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