



Comparative Study of CO₂ Storage Capacity Estimation in Depleted Oil & Gas Reservoir: A Case Study in Vermillion Basin Gulf of Mexico

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Abstract

CO₂ emissions rates have seen an exponential growth from the 19th century up till date, if no drastic measures and plans are implemented to prevent this exponential growth the consequence will be devastating. The notion of achieving net-zero greenhouse gas emissions gained prominence through the Paris Agreement, a groundbreaking accord reached at the United Nations Climate Change Conference. This agreement was devised to mitigate the impact of greenhouse gas emissions. To execute the net-zero CO₂ emission plan, the USDOE has set a new goal to remove gigatons of carbon dioxide (CO₂) from the atmosphere and durably store it for less than \$100/ton of net CO₂-equivalent. Making such a goal a reality requires an accurate estimation of CO₂ storage capacity for the successful implementation of Carbon Capture and Storage (CCS) technologies, and the assessment of the impact of CCS to the reduction of CO₂ emissions.

Hence this paper serves as a template for accurately estimating CO₂ storage capacity in depleted saturated oil reservoirs with initial gas cap using three approaches: Volumetric, Production and Correlation-based methods and compares the accuracy of the estimates. A case study was conducted on a depleted VR273_Q combination sand in the Vermillion Basin, Gulf of Mexico (GOM).

The deterministic and stochastic (P50) CO₂ storage capacity estimates from the Volume-based method are 1.21 million tonnes (Mt) and 1.23 Mt respectively, while the deterministic CO₂ storage capacity estimates from the Production and Correlation-based method are 1.32 Mt and 1.41 Mt respectively. All three approaches showed similar results, with little deviations attributed to petrophysical uncertainties arising from data gaps i.e., absence of well logs to key wells. However, these uncertainties are captured by Stochastic (P90) CO₂ storage capacity estimates of 1.47 Mt from the Volume-based method. Although the Correlation-based approach slightly overestimates the CO₂ storage capacity, it can be used as a starting point for quick estimation as it only requires production data which are readily available on various databases for GOM. Finally, through this paper, opportunities for concerned agencies to make well-informed energy-related policies and business decisions are made possible.

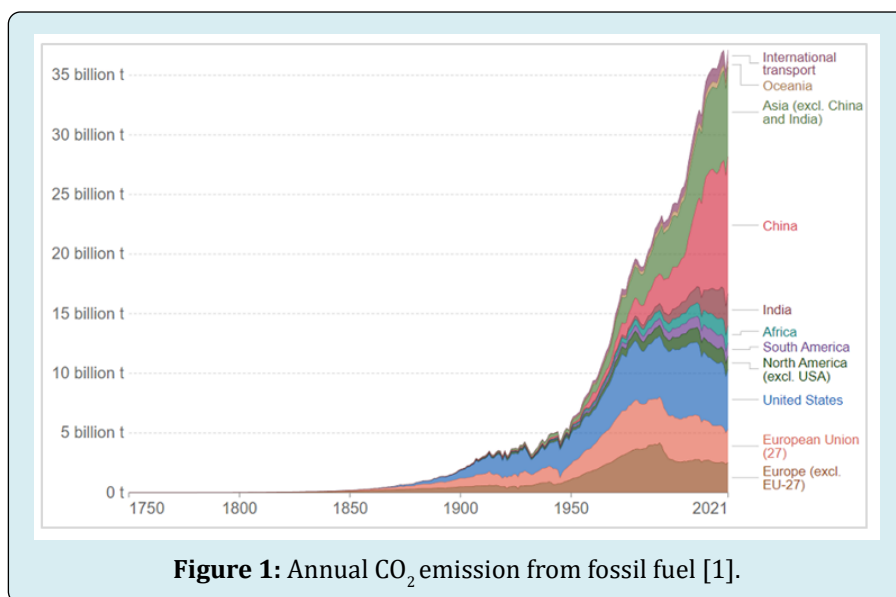
Keywords: CO₂ Storage; Sequestration; Volumetric; Depleted Reservoirs; Gulf Of Mexico; Vermillion Basin

Abbreviations: CCS: Carbon Capture and Storage; GOM: Gulf of Mexico; GHG: Greenhouse Gases; OWL: Offshore Well and Lease; SONRIS: Strategic Online Natural Resources Information System; BOEM: Bureau of Ocean Energy Management; BHP: Bottom Hole Pressure; HCRF: Hydrocarbon Recovery Factor; CSLF: Carbon Sequestration Leadership Forum; GG: Geology and Geophysics GG; OGIP: Original Gas Initially in Place; OOIP: Original Oil Initially in Place.

Introduction

CO₂ emissions are primarily caused by the combustion

of fossil fuels, both in large combustion units like those used in electric power generation and in smaller, more dispersed sources like automobile engines and furnaces used in residential and commercial buildings. Some industrial and resource extraction processes, as well as open burning during land clearance, emit CO₂. Global world CO₂ emissions from fossil fuels in 1950 was about 6 billion tonnes of CO₂ with Europe and United States accounting for more than 85% of emissions each year, but now emissions have skyrocketed to over 34 billion tonnes per year due to the rise in emissions in the rest of the world particularly in Asia, notably China and India. The US and Europe now account for just under one-third of emissions.



Due to changing global climates caused by the uncontrolled emissions of greenhouse gases (GHG), the United States Department of Energy, Policymakers both in the U.S and around the world are now encouraging the deployment of Carbon Capture and Storage (CCS) technology to help curb CO₂ emissions from fossil fuels.

Global assessments of CO₂ storage opportunities involving large volumes of CO₂ storage have focused on the options of geological storage such as depleted oil and gas reservoirs, deep saline formations and coal beds etc [2-5].

Depleted oil and gas reservoirs are one the most sorted candidates for geologic CO₂ storage because most Oil and Gas fields and basins have been previously studied and some are currently being studied, hence there are rich databases to support CO₂ storage studies. Studies show that the trap mechanisms of most depleted oil and gas reservoirs demonstrate structural integrity and safety as they have been able to keep the hydrocarbons for millions

of years without leaks. Also, there are numerous reservoir engineering software that can readily be modified to monitor CO₂ if stored in depleted oil and gas reservoirs. Finally, the economics of injecting CO₂ into depleted oil and gas reservoirs are relatively cost-effective when compared to other storage options as there are existing infrastructure such as wells, pipelines, etc. to handle CO₂ storage operations [6,7].

Depleted oil and Gas CO₂ storage sites can be located onshore or offshore; however, offshore storage sites have the advantages of lowered dangers of potential contaminating sources of water for drinking, reduced surface and mineral rights issues, and access to existing offshore infrastructure and pipeline transportation routes.

There are site selection criteria for geologic CO₂ storage. Firstly, the storage formation has to be a seal mechanism and leak-free to prevent upward migration of CO₂ to the surface thereby contaminating surface groundwater. The storage

formation must be deep enough (> 800 m) to keep CO_2 at a supercritical state as this allows for the storage of more CO_2 , and not exceeding 2500m for economic purposes. Also, the storage site of interest must be large enough to hold a sizable amount of injected CO_2 [8,9].

There is limited data on the assessment of CO_2 storage capacity of depleted oil and gas fields, hence, this work will serve as a template for quick yet detailed and accurate estimates of CO_2 storage capacity for potential depleted hydrocarbon sites. An accurate estimation of the storage capacity is required for the government's energy-related policies and business decisions, the successful implementation of CCS technologies, and the assessment of the impact of CCS to the reduction of CO_2 emissions.

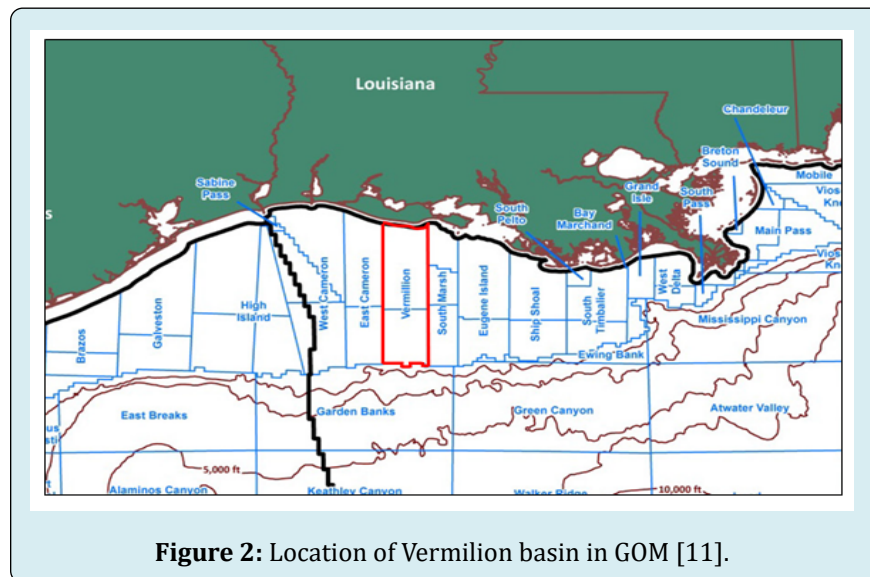
In the following sections of this paper, an overview of the Vermilion basin in the Gulf of Mexico where potentially depleted oil and gas fields are located is presented. Methodologies for estimating CO_2 storage capacity using volumetric, production, and correlation-based methods are also presented. A Case study for estimating CO_2 Storage capacity in a depleted saturated oil reservoir with gas cap using all three methods is presented. Results comparing the estimates are made and finally, conclusion and recommendation are highlighted.

Field Overview Vermilion Basin, Gulf of Mexico

The Gulf of Mexico (GOM) is the third most prolific petroleum basin in the world formed because of the opening of the Atlantic Ocean. It is located at the southeast shores of the United States bordered by Texas, Louisiana, Mississippi, Alabama and Florida.

According to the Estimated Oil and Gas Reserves, Gulf of Mexico Region, December 31, 2019 report, there are a total of 1325 oil and gas fields in the federally regulated part of GOM with original reserves estimates of 26.77 bbl of Oil and 197.0 Tcf of gas. Cumulative Production from the fields accounts for 22.12 bbl of Oil and 190.9 Tcf of gas. There are 911 depleted fields which represent 68.8 percent of all fields and 414 active fields with estimated reserves of 4.65 bbl of Oil and 6.1 Tcf of gas [10].

Blocks in the Vermilion basin lie in the GOM approximately 102 miles from the coast of Louisiana in the continental shelf (Figure 2) below. The deposition of river-fed sediments on enormous volumes of a mobile substrate greatly influences the structural nature of GOM (salt). Growth faults and roll-over anticlines describe the trapping style in the Vermilion Basin.



The Vermilion basin is predominantly a gas basin with pockets of oil and combination reservoirs (Oil reservoirs with initial gas cap). According to the (OWL, 2022) database, the basin contains 12 actively producing fields and 75 already depleted fields and has so far produced a cumulative oil production of 592MMbbl and a cumulative gas production of 16,751 Bcf. This makes it a prospective candidate for underground carbon sequestration.

Static CO_2 Storage Capacity Estimation Approach

In this study, three approaches will be undertaken to estimate the static CO_2 storage capacity of the depleted hydrocarbon reservoir.

They include the.

1. Volumetric-based approach.

2. Production-based approach.
3. Correlation-based approach.

Volumetric Based Approach for CO₂ Storage Capacity Estimation

The USDOE proposed a volumetric approach for CO₂ storage capacity estimation. The volumetric estimate is based on the industry standard method for calculating OOIP and OGIP by the formation volume factor [12].

The volumetric-based equation is given below as.

$$G_{CO_2} = Ah\phi(1 - S_{wi})B\rho_{CO_2}E_{Roil/gas} \quad (1)$$

Where, G_{CO_2} is the mass of CO₂ (tonnes), A is the reservoir area (m^2), h is the net thickness (m), ϕ is the average effective porosity (fraction), S_{wi} is the initial water saturation (fraction), B_{oi} is the initial oil or gas formation volume factor (m^3/m^3), B_{gi} is the initial gas formation volume factor (m^3/m^3), ρ_{CO_2} is the standard CO₂ density (Kg/m^3), $E_{Roil/gas}$ is the CO₂ storage efficiency (fraction), representing a fraction of the total pore volume from which oil and/or gas

was produced and can be supplied with CO₂. The CO₂ storage efficiency can be calculated using reservoir simulations or CO₂ - Enhanced Oil Recovery experience [12].

Another Volumetric method for estimating CO₂ storage capacity in depleted hydrocarbon reservoirs was proposed by CSLF [13]. Petrophysical properties such as reservoir net thickness, porosity, water saturations, etc., depending on the field or basin of study can be obtained from publicly available databases such as Offshore Well and Lease (OWL), Strategic Online Natural Resources Information System (SONRIS), and Bureau of Ocean Energy Management (BOEM) etc.

The geothermal gradient of the reservoir of study can be estimated from the well log data, pressure gradient can be estimated from Bottom Hole pressure (BHP) reports, and they are available in public data sources. If temperature and pressure data at targeted depth for the given reservoir are not available as input for CO₂ density estimation using the Peng-Robinson equation of state [14] or Modified Peng-Robinson equation, the temperature and pressure gradient can be utilized. There are also correlations for estimating CO₂ density as a function of depth and temperature [15,16] (Figure 3) below.

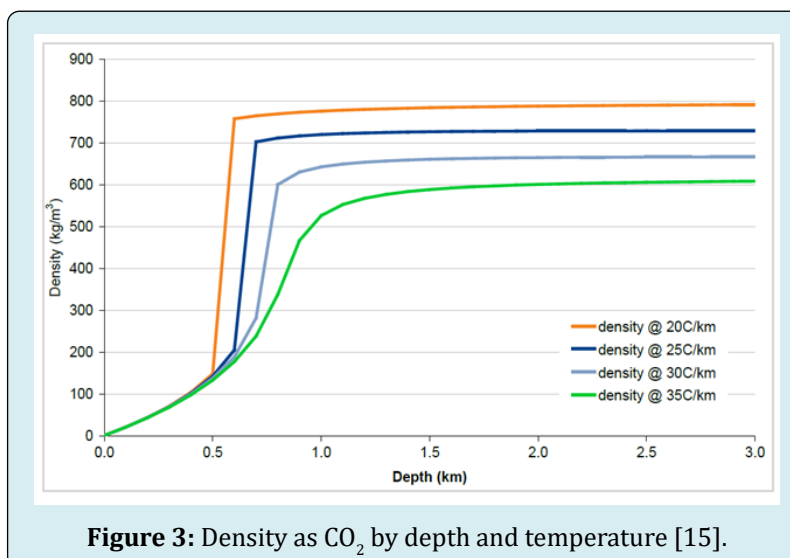


Figure 3: Density as CO₂ by depth and temperature [15].

In order to store CO₂ in a number of depleted gas, oil, and combination reservoirs in the Gulf of Mexico, [7] carried out CO₂ Injection modeling tests. The improved quantification of the CO₂ storage amounts was addressed using the numerical simulator Cozsim and its graphical user interface Cozview, which were created [7]. Cozsim is a completely implicit, finite difference-based, extended black oil reservoir flow simulator that was created by NITEC LLC with support from the Department of Energy. It features three phases (oleic, gaseous, and aqueous), four components (oil, water, hydrocarbon gas, and carbon dioxide).

For the majority of the sands, 20,000 MSCF/d was the maximum carbon dioxide injection rate per well. This injection rate has no effect on the reservoir's eventual CO₂ storage volume; rather, it merely affects how long it takes for the reservoir to become full with carbon dioxide. These restrictions were applied to an estimated case until the minimum field injection rate limitation of 100 MSCF/d was met.

Consequently, a plot of CO₂ storage efficiency was developed, $E_{Roil/gas}$ against Hydrocarbon recovery factor

(HCRF) see Figure 4. $E_{oil/gas}$ is calculated using the USDOE equation (1).

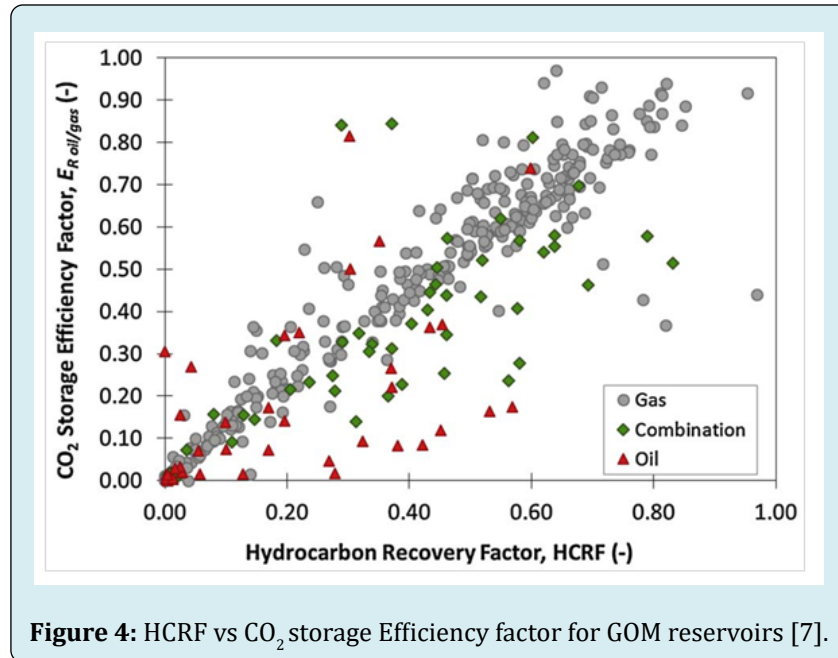


Figure 4: HCRF vs CO_2 storage Efficiency factor for GOM reservoirs [7].

Mathematically, HCRF is expressed as

$$HCRF = \frac{(Cum.Oil Prod. \times B_{oi} \times 5.615) + (Cum.Free Gas Prod. \times B_{gi})}{(OOIP \times B_{oi} \times 5.615) + (OGIP \times B_{gi})} \quad (2)$$

Where OOIP is the Original Oil initially in place (STB), OGIP is the Original Gas initially in place (SCF), B_{oi} and B_{gi} is the initial oil or gas formation volume factor (RBBL/STB and RCF/SCF), For the oil reservoirs, the HCRF is equal to the ratio of cumulative produced oil and OOIP as OGIP and B_{gi} are "0". For the gas reservoirs, OOIP and B_{oi} are "0".

Production Based Approach for CO_2 Storage Capacity Estimation

The Carbon Sequestration Leadership Forum (CSLF) proposed a production-based approach for CO_2 storage capacity estimation which is based on OGIP for gas reservoirs and OOIP for oil reservoirs at surface conditions [12,13].

The Production-Based equation given below as.

$$\text{For Oil, } G_{CO_2oil} = \rho_{CO_2} \left[\frac{R_f OOIP}{B_{oi}} - V_{wi} + V_{wp} \right] \quad (3)$$

$$\text{and Gas, } G_{CO_2gas} = \rho_{CO_2} R_f (1 - F_{IG}) OGIP * B_{gi} \quad (4)$$

Where, G_{CO_2} is the mass of CO_2 (Tonnes), OGIP is the Original Gas Initially in Place (m^3), OOIP is the Original Oil Initially in Place (m^3), B_{gi}/B_{oi} is the initial gas and oil formation volume factor (m^3/m^3), ρ_{CO_2} is the standard CO_2 density (Kg/m^3), F_{IG} is the fraction of injected gas (fraction), V_{wi} is the volume of injected water (m^3), V_{wp} is the Oil or gas recovery factor (fraction). F_{IG} is "0" when there is no injected gas. Similarly, V_{wi} and V_{wp} are both "0" when there is no injected or produced water.

Correlation-Based Approach for CO_2 Storage Capacity Estimation

Based on the simulation of CO_2 injection volumes for all 359 gas, 34 oil, and 68 combination sands in GOM, [7] developed a Production- CO_2 Storage Correlation for estimating CO_2 storage capacity in depleted gas, Oil, and combination reservoirs in GOM. Strong correlation with R-Squared value of above 0.96 is seen across the different reservoir types in Figure 5 below.

The slope of the correlation line is different for each reservoir type. This is due to the high compressibility and mobility of gas when compared to oil. As more CO_2 injection was observed in gas sands for the same production volumes, whereas CO_2 storage volumes decreased from gas to combination sands, and combination sands to oil sands.

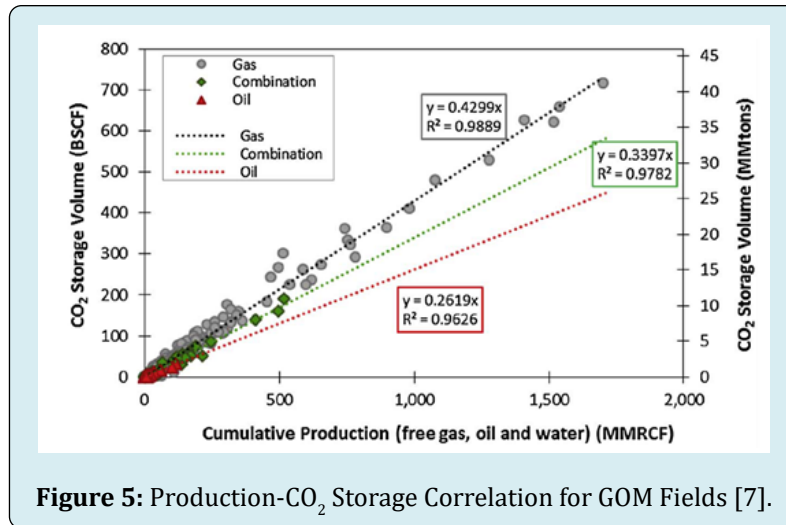


Figure 5: Production- CO_2 Storage Correlation for GOM Fields [7].

Equations (5-8), explain the relationship between the slopes, dependent and independent variables, and their units of conversion.

From the correlation, y , the dependent variable, is the CO_2 storage volume at standard conditions (BSCF), and x the independent variable, is the cumulative production at reservoir conditions (MMRCF).

- **Gas Sands**

$$\text{CO}_2 \text{ Storage Vol. (BSCF)} = 0.4299 \times \text{Cum. Production (MMRCF)} \quad (5)$$

- **Oil Sands**

$$\text{CO}_2 \text{ Storage Vol. (BSCF)} = 0.2619 \times \text{Cum. Production (MMRCF)} \quad (6)$$

- **Oil and Gas Combination Sands**

$$\text{CO}_2 \text{ Storage Vol. (BSCF)} = 0.3397 \times \text{Cum. Production (MMRCF)} \quad (7)$$

$$\text{CO}_2 \text{ Storage Vol. (MMtons)} = 0.0575 \times \text{CO}_2 \text{ Storage Vol. (BSCF)} \quad (8)$$

Equation (8) below converts CO_2 storage volume at standard conditions from BSCF to MMtons or Mt.

$$\text{CO}_2 \text{ Storage mass. (MMtons)} = 0.0575 \times \text{CO}_2 \text{ Storage Vol. (BSCF)} \quad (8)$$

Case Study

The volumetric, production, and correlation-based methods were used in estimating the CO_2 storage capacity in VR273_Q, a depleted combination reservoir i.e., a saturated oil reservoir with initial gas cap in the Vermillion Basin, GOM. Table 1 below obtained from the 2019 sand report of BOEM database under the Geology and Geophysics (G&G) section, shows 7 wells that drained the VR273 sands.

Boem Field	Lease	Area Code	Block	Well	Pic	Well	Play	Sand	Oper Res
VR273	G14412	VR	273	1.77E+11	S01	A001	PLL-P1	Q	ANGB "Q"
VR273	G14412	VR	273	1.77E+11	S01	A001	PLL-P1	Q	ANGB "Q"
VR273	G23829	VR	272	1.77E+11	S01	B001	PLL-P1	Q	R SAND
VR273	G23829	VR	272	1.77E+11	S01	B002	PLL-P1	Q	Q SAND
VR273	G23829	VR	272	1.77E+11	S01	C001	PLL-P1	Q	Q Sand
VR273	G24872	SM	102	1.77E+11	S03	A001	PLL-P1	Q	Q
VR273	G24872	SM	102	1.77E+11	S01	A006	PLL-P1	Q	Q2 Sand

Table 1: Well information for the VR273_Q sands [10].

The VR273_Q production, sand and fluid properties obtained from the BOEM database are presented in Tables 2,3 respectively. Additional digital well log data from some of the wells in table 1 above were obtained from the OWL database. Petrophysical estimates were made from available well logs

using Techlog petrophysical software, to help capture wide ranges of sand and fluid uncertainties of VR273_Q during volume calculations. Uncertainty analysis capturing the ranges of some of the rock and fluid properties were entered in the crystal ball software for stochastic volume estimates.

BOEM Reported Reservoir and Fluid Parameters	Sand, VR273_Q
OOIP (MMSTB)	26.34
OGIP (BSCF)	15.35
Cumulative oil Production (MMSTB)	1.92
Cumulative gas Production (BSCF)	9.61
Subsea depth, SS (ft)	4087
Total average net thickness (ft)	30.54
Total Area (acres)	730
Oil total thickness (ft)	36.71
Oil total area (acres)	381
Gas total thickness (ft)	23.81
Gas total area (acres)	349
Porosity (frac)	0.34
Residual Water Saturation (frac)	0.2
Permeability (mD)	1558
Initial Pressure (Psia)	2034
Initial Temperature (°F)	115
Pressure Gradient (psia/ft)	0.494
Temperature gradient (°F/100ft)	1.101
Initial gas formation volume factor, B _{gi} (RCF/SCF)	0.0062
Initial oil formation volume factor, Boi (RBBL/STB)	1.177
Gas Oil ratio, GOR (MSCF/STB)	4.636

Table 2: Production, rock, and fluid Properties for the VR273_Q sand [17].

VR273_Q Properties	Low Case	Base Case	High Case	Units
Gas Cap Area	1,341,780	1,412,400	1,483,020	m ²
Gas Cap Height	6.89	7.26	7.62	m
Oil Rim Area	1,464,805	1,541,900	1,618,995	m ²
Oil Rim Height	10.63	11.19	11.75	m
Porosity	0.29	0.34	0.37	fraction
Saturation	0.15	0.2	0.3	fraction
B _{gi}	-	0.0062	-	m ³ /m ³
B _{oi}	-	1.177	-	m ³ /m ³

Table 3: Uncertainty Range of VR273_Q structural and reservoir properties.

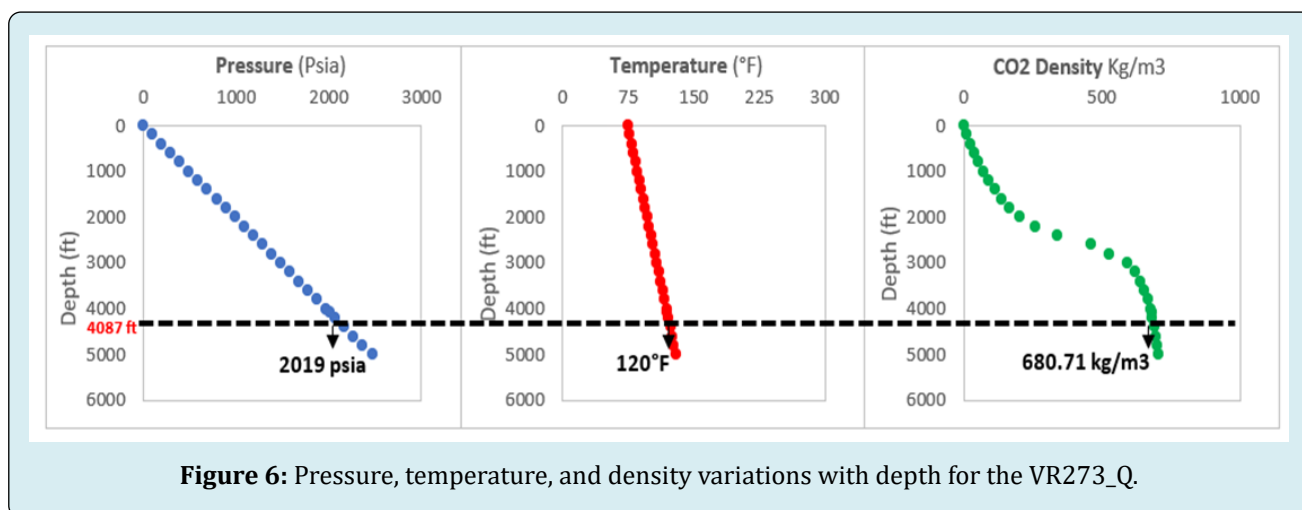
Results

Volumetric-Based Approach

Parameters for input into the USDOE equation i.e Equation (1) such as gas cap area and thickness, oil area and thickness, oil and gas formation volume factors, porosity and residual water saturations data are obtained from Table 2.

Pressure and temperature values of about 2019 psia and 120°F were calculated at the average reservoir depth of 4087ft using pressure and temperature gradients of 0.494 psia/ft and 1.101°F/100ft respectively obtained from Table 2.

The Modified Peng-Robinson equation [18] uses the estimated pressure and temperature as input was used to estimate the CO₂ density of 680.17 Kg/m³. see Figure 6 below, for graphical analysis of temperature, pressure, and CO₂ density.



CO₂ Storage efficiency is obtained from Figure 4: the HCRF vs CO₂ storage Efficiency factor plot for GOM reservoirs. From Equation 2, Hydrocarbon Recovery Factor (HCRF) was estimated to be 0.27. The low HCRF value is due to the very low recovery from the Oil portion of the reservoir caused by most of the production of the Gas cap and solution gas in the depletion drive mechanism. The CO₂ storage Efficiency factor was found to be 0.32.

Using the volumetric-based equation from Equation (1), and corresponding reservoir parameters from Table 2, the deterministic Static CO₂ storage capacity was determined to be 1.21 million Tons (Mt). To obtain a Stochastic Static CO₂ storage capacity, we considered the range of porosity values from 0.29 to 0.37 and saturation range of 0.15 to 0.3 as seen by wells in the VR273_Q sand. The Area and height of the VR273_Q oil and Gas cap were varied by a ±5% from its base value in order to account for structural uncertainty see Table 3 for details. The estimated P90, P50 and P10 Stochastic Static CO₂ storage capacity mass obtained are 1.04, 1.23 and 1.47 million Tons (Mt), respectively. Table 4 summarizes the estimated deterministic and Stochastic Static CO₂ Storage capacity.

Results				Units
Deterministic	1.21			Mt
Stochastic	P90	P50	P10	Mt
	1	1.2	1.5	

Table 4: VR273_Q Estimated CO₂ Storage Capacity Volume (Volume-based approach).

Production-Based Approach

Parameters for input into the CSLF equations i.e Equations (3-4) such as Original Gas Initially in Place (OGIP), Original Oil Initially in Place (OOIP) [19], oil and gas formation volume factors data are obtained from Table 2. Recovery factors for oil and gas cap segment of the reservoir are estimated to be 7.3% and 62.5% respectively, standard CO₂ density has been estimated to be 680.71 Kg/m³. Fraction of injected gas, volume of injected and produced water are set to is "0". Finally, the deterministic Static CO₂ storage capacity was determined to be 1.32 million Tons (Mt).

Correlation Based Approach

Firstly, the cumulative oil and gas production at surface conditions from the Table 2 were both converted to reservoir conditions by multiplying with their respective formation volume factors [20]. Next their units were both harmonized into reservoir cubic feet (MMRCF) and summed up. The total cumulative oil and gas produced at reservoir conditions was

estimated to be 72.3 MMRCF.

Secondly, Equation (7) from the Oil and gas combination sands correlation in Figure 2, transforms the total cumulative oil and gas produced at reservoir conditions of 72.3 MMRCF to CO₂ storage volume at surface conditions of 24.56 BSCF. Finally, CO₂ storage volume of 24.56 BSCF is converted to mass in tonnes using eqs.8. CO₂ storage capacity was estimated to be 1.41Mt (million tonnes).

Discussion of Results

The three approaches for estimating the CO₂ storage for depleted saturated oil reservoir with gas cap) shows similar results. The table below shows summaries of the results Table 5.

Method	Deterministic (Million tonnes)	Stochastic (P50) (Million tonnes)
Volumetric -based	1.21	1.23
Production -based	1.32	-
Correlation-based	1.41	-

Table 5: Summary of Estimated CO₂ Storage Capacity Volume.

The CO₂ storage capacity estimated by the production-based and correlation-based methods deviates from the estimated Volumetric Methods (P50) by 7.3% and 14.6% respectively. These deviations could be attributed to the petrophysical uncertainties arising from data gaps i.e., absence of well logs for some key wells. The volumetric estimation is subject to some degree of uncertainty due to the stochastic P50 approach. It takes into account a range of potential parameter values, recognizing the inherent variability in geological settings. Although the Correlation-based approach tends to overestimate volumes, estimates are reasonably accurate and use only production data. Reservoir and fluid properties data are not required for its use [21,22].

Limitations

1. Water encroachment from an aquifer was not considered in this study. Potential water encroachment could ultimately affect the CO₂ storage Efficiency factor.
2. Production estimates may change for wells that are producing at the time of this research. However, at the time of the computations, only about 7% of the oil in place had been recovered. Consequently, it could be necessary to modify the production statistics; nevertheless, this does not significantly impair the projected capacity of

CO₂ at any given moment.

3. The simulated model is limited to fields that are in GOM.

Conclusion

Three methods for estimating Static CO₂ storage Capacity namely the Volumetric, Production and Correlation methods were applied to the depleted combination reservoir (Oil with Gas cap) of VR273_Q in the Vermillion Basin, GOM. The estimates showed similar results, with little deviations attributed to petrophysical uncertainties arising from data gaps i.e., absence of well logs to key wells [23]. Material Balance concept is established between the estimated CO₂ storage capacity by the Volumetric-based approach and Production-based approach as both methods show very similar results. The correlation-based method is very easy to use and relies only on production data, however it tends to overestimate the CO₂ storage capacity slightly. Through this study, opportunities for accurately finding and quantifying potential CO₂ storage sites within the GOM and worldwide abound. Finally, an accurate estimation of the storage capacity is required for the government's energy-related policies and business decisions, the successful implementation of CCS technologies, and the assessment of the impact of CCS to the reduction of CO₂ emissions etc.

Recommendations

Researchers can utilize this work as a template for quick yet detailed and accurate estimates of CO₂ storage capacity using all three methods for potential depleted hydrocarbon sites.

The Correlation-based approach is reasonably accurate and can be used in the absence of reservoir and fluid properties data (only production data are needed). The Correlation-based approach used in this study is fitted for depleted gas, oil, and combination reservoir fields in Gulf of Mexico (GOM), researchers can focus on developing regional correlations for estimating CO₂ storage capacity from other underground CO₂ storage sources. Properties of depleted reservoirs frequently vary spatially. Refinement of storage capacity estimations can be achieved by accounting for these heterogeneities using advanced geological models. Additionally, Injecting CO₂ may result in pressure variations and possible seismic hazards. For safe and efficient storage, geomechanical studies and wellbore integrity evaluations are essential.

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Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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