CO_2-EOR as a Carbon Capture Utilization and Storage (CCUS) Method

Identifying candidate oil reservoirs for miscible CO_2 Enhanced Oil Recovery (CO_2-EOR)

The initial stage of oil reservoir development involves utilizing their natural energy, a process also referred to as natural depletion or primary production mechanism. Once the reservoir energy is exhausted, it is necessary to pressurize the reservoir to achieve additional oil production. In such methods, which are commonly known as secondary mechanism or recovery, the oil can be swept with water injection (waterflooding) or gas injection (gas flooding).

Enhanced Oil Recovery (EOR) methods are implemented to further produce residual oil left in the reservoir after primary and secondary recovery. One EOR scheme consists of injecting CO_2 at high pressures and rates to sweep the remaining oil in the reservoir. Miscible CO_2 flooding can be achieved when the CO_2 and oil form a single phase in the reservoir. This is desirable since the mobility of the oil is typically increased under such conditions leading to higher production.

During this injection and sweeping process, a portion of the injected CO_2 is trapped within the reservoir, storing it underground. This has brought CO_2-EOR to the forefront to increase oil production and perform permanent storage simultaneously. Therefore, operators are increasingly interested in finding the right reservoir candidates to implement such methodology.

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CO_2-EOR Workflow

Main aspects, considerations, and assumptions

The CO_2-EOR dashboards in EDIN are meant to be used as a workflow to identify oil reservoirs that can be candidates for miscible CO_2-EOR and facility emission sources that can be used to supply the required volumes of CO_2.

An estimate of the potential recovery (P50 cumulative production distribution and curves) is provided at a given injected volume of CO_2 expressed as percent hydrocarbon pore volume (%HCPV). Analytical probabilistic curves are used to describe the potential additional oil Recovery Factor (R_f%), the CO_2 Net Utilization Factor (U_f in Mscf/STB) and the product of both (R_f x U_f). The product of these terms has a direct impact on the potential CO_2 reservoir storage (M_{CO_2} in Mt).

The following are considerations of this study and scenarios that are not covered by the currently implemented methodology:

- There is no differentiation between offshore and onshore assets. Similarly, at the present time, topography is not considered.
- Only emission sources with reported values after 2019 were used.
- The average of the last three years of emissions is used as a proxy for expected future emission volumes and is assumed to be constant.
- Only emission sources with an emission rate greater than 0.01 Mt/Year were considered.
- This methodology cannot be used to evaluate additional production or storage in gas reservoirs.
- It takes no account of existing pipeline infrastructure.
- It does not assess the quality of existing boreholes.
- It eliminates reservoirs in fields that do not meet minimum reservoir criteria by using a score system (see Table 1 in next section).
- It eliminates reservoirs that could not be sourced from existing emissions hubs.
- Where data is missing, values are imputed (formulas are outlined at the end of the document).

Parameter definition and oil reservoir screening criteria

Scoring system

Table 1 contains the parameter (feature) scoring for each reservoir and fluid attribute considered for the CO_2-EOR screening test. This list comes after an extensive literature review of reported CO_2-EOR schemes that are successful. The feature score range goes from 1 to 5 where the higher the number the higher the importance of the given property.

Table 1. Scoring by reservoir parameter and its corresponding range of values

Reservoir Characteristic (Feature)	Suitable for miscible CO_2-EOR		Score
	Min	Max	
Depth (ft)	1600	13365	1
Oil Gravity (°API)	22	45	5
Temperature (°F)	82	260	1
Oil Viscosity (cP)	–	6	3
Pressure (psi)	MMP	–	5
Initial pore pressure gradient (psi/ft)	–	0.74	1
Porosity (%)	3	37	1
Initial oil saturation (%)	26.5	–	1
Initial pore space oil saturation	0.05	–	1
Original oil in place (MMSTB)	12.5	–	1
Remaining oil fraction in the reservoir (%)	20	–	1
Remaining oil in the reservoir (MMSTB)	5	–	3

In this study, only reservoirs with the following fluid type and production classification (values in EDIN) are considered:

- Fluid type equal to:
  - "Oil"
  - "Oil,gas"
  - "Oil,gas,cond"
- Production type is not:
  - "Prod, enhanced recov"
  - "Abd,no improved recv"
  - "Abd aft imprvd recov"
  - "Abd aft enhncd recov"

Each reservoir is evaluated individually based on its properties. If a value falls within the range suitable for CO_2-EOR as outlined in Table 1, the corresponding score from the table is assigned to it. If not, a value of zero is designated. When a value is missing from a required reservoir characteristic, the reservoir is not immediately discarded. Instead, it is assumed that the variable at hand falls within the acceptable range and the corresponding importance score is assigned to it. Finally, reservoirs with a total score of 19 or higher are considered that pass the screening criteria.

Once the parameters from Table 1 are evaluated for each reservoir, a plot is prepared where blue is assigned if the reservoir has a feature within the required range for CO2-EOR feasibility. Reservoirs are then sorted by the number of features and their importance. The resulting plot is shown in Figure 1.

Figure 1. Example of reservoir properties scoring plot for reservoirs that passed the screening

From Figure 1, the reservoirs that have the most reservoir parameters within range are located on the left part of the plot. As one moves through the plot in Figure 1 from left to right, reservoirs start to have fewer parameters within range but have enough of them to pass the reservoir screening test.

A similar plot can be prepared for reservoirs that fail the reservoir screening test. Figure 2 summarizes the reservoirs that do not have enough reservoir properties within range and, therefore, have failed the screening test.

Figure 2. Example of reservoir properties scoring plot for reservoirs that failed the screening

Estimating storage capacity and potential incremental oil recovery factor

The CO_2 storage capacity is then calculated for every reservoir that passes the screening process. The following equations are used to calculate potential CO_2 storage, additional (incremental) recovery factor and net utilization factor (Bachu, 2016):

$$M_{CO_2} = 0.00052 \times U_f \times R_f \times OOIP \quad (1)$$

$$U_f = \frac{1}{10^6} \frac{V_{CO_2 purchased}}{N_p} \quad (2)$$

$$R_f = \frac{N_p}{OOIP} \quad (3)$$

where:

U_f	*Net CO_2 utilization factor, Mscf/stb*
$V_{CO_2 purchased}$	*Cumulative volume of purchased CO_2 injected, Mscf*
N_p	*Cumulative incremental oil production, MMstb*
$OOIP$	*Original oil in place, MMstb*
R_f	*Incremental oil recovery, %*
M_{CO_2}	*Potential CO_2 storage, Mt*

Using these expressions, a set of probabilistic plots are created at different percent hydrocarbon pore volumes (%HCPV) for R_f and U_f (refer to Azzolina et al, 2015). Additionally, an R_f x U_f plot is presented to better understand how this multiplication affects the potential CO_2 storage (as shown in Equation 1).

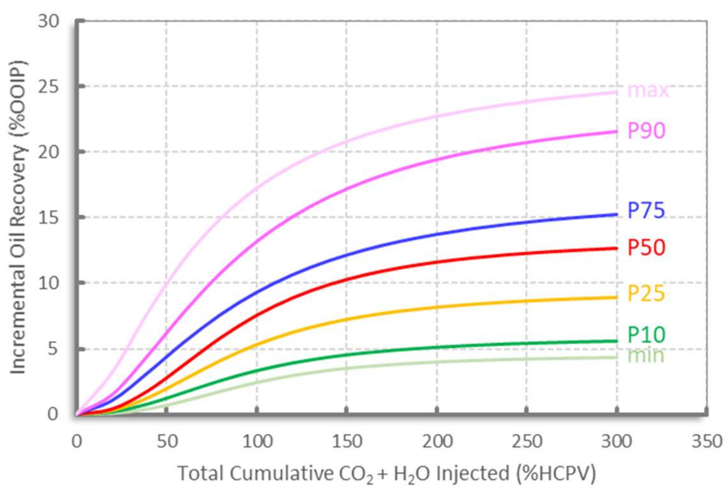

Figure 3. Incremental Oil Recovery (%OOIP) vs Total Cumulative CO_2 + H_2O Injected (%HCPV)

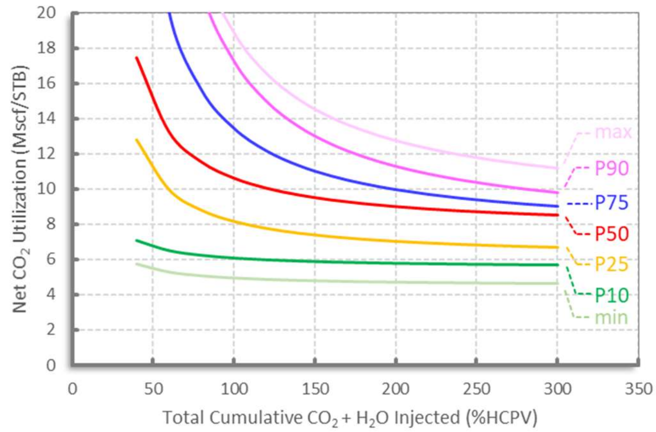

Figure 4. Net CO_2 Utilization (Mscf/STB) vs Total Cumulative CO_2 + H_2O Injected (%HCPV)

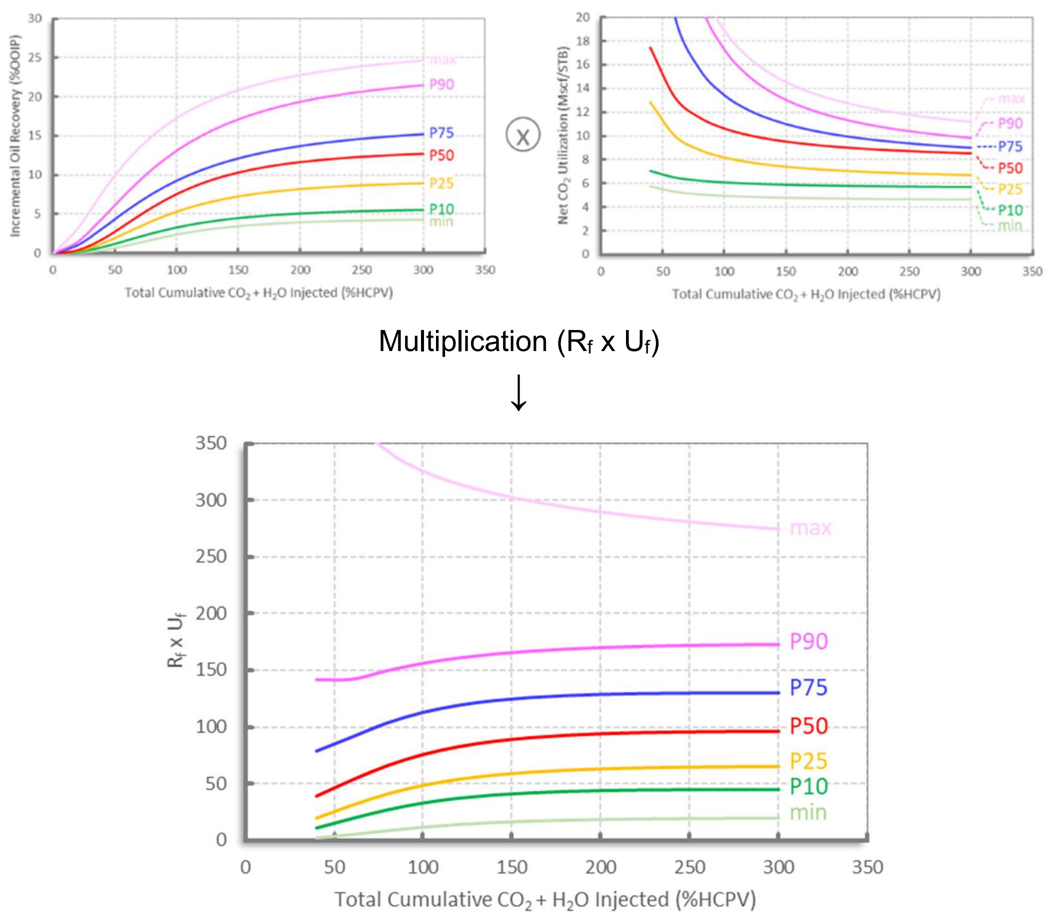

Figure 5. R_f x U_f vs Total Cumulative CO_2 + H_2O Injected (%HCPV)

All probability curves are shown for completeness but, for the purposes of the reservoir and facility emission source analysis, only P50 curves are considered.

Considering a CO_2-EOR 200% HCPV scheme for reservoirs with a score of 20 or more (1), following the previous steps, we can quickly find the top reservoirs in the United States (2) that have the highest potential additional oil recovery (3). We can then narrow or expand our search with considerations such as potential CO_2 storage, location (onshore/offshore), or rank them by a specific parameter such as total score, oil viscosity, oil API, etc.

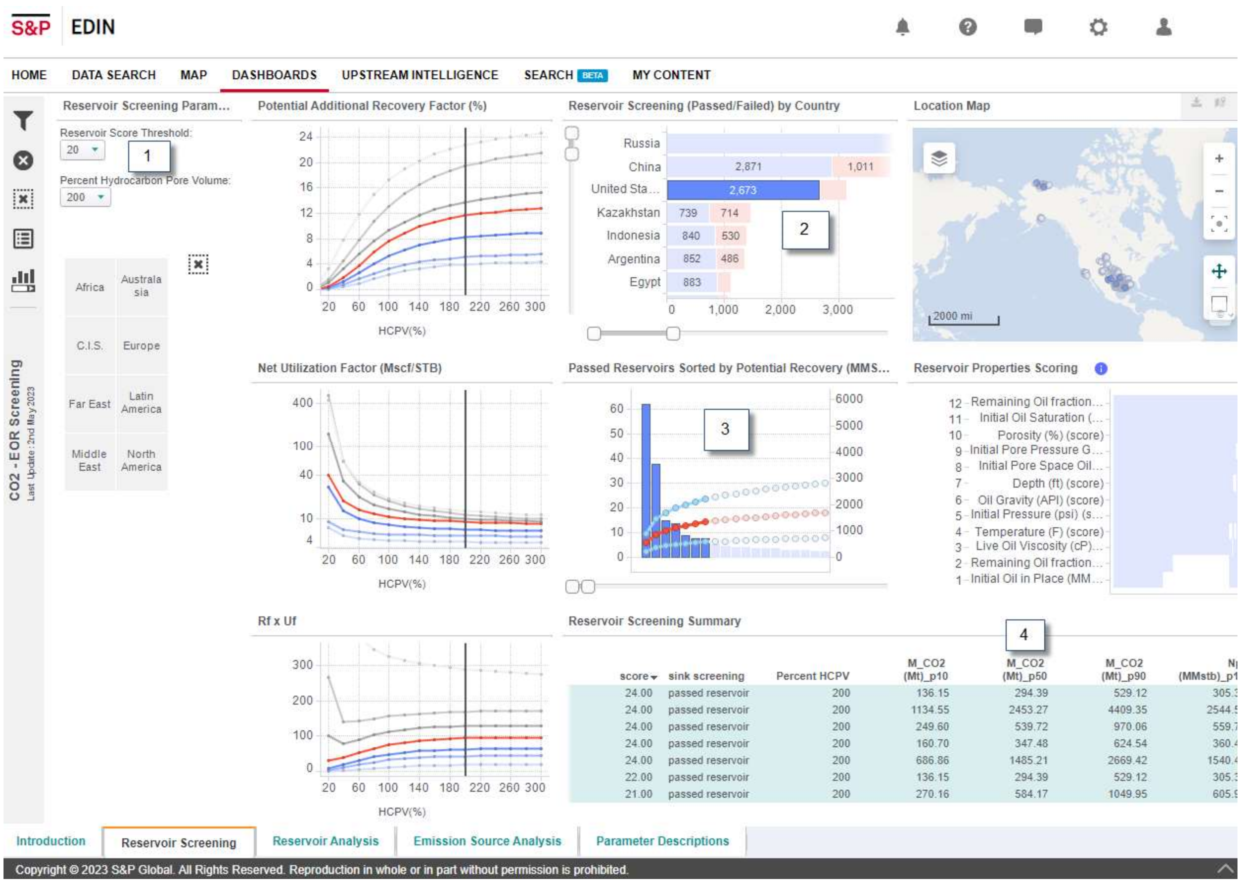

Figure 6. Reservoir screening dashboard: Finding reservoirs with highest potential additional oil recovery

Linking Emission Sources and Reservoirs

To have a better understanding of the relationship between a CO_2 emitter (emission source) and the storage capacity of a reservoir (to act as CO_2 sink), one can analyze each pair of source-sink nodes starting from the perspective of each of them.

Facility Emission Source Analysis

Starting from the point of view of the emitter, the estimation of the time (years) required for a particular emission source to reach the maximum storage capacity (in Mt) of an oil reservoir (for an EOR scheme) is expressed using the following equation:

$$A_{ER} = \frac{M_{CO_2}^{R}}{q_E} \tag{4}$$

Therefore, the higher A_{ER} the better the capacity to store more CO_2 underground over time.

For an impartial comparison, three normalized parameters are used. The normalized capacity index for each reservoir is calculated using the minimum and maximum with reference to each country by:

$$C_{ER}^{N} = \frac{A_{ER} - A_E^{min}}{A_E^{max} - A_E^{min}} \tag{5}$$

Similarly, the normalized distance between the emitter and the oil reservoir is calculated by:

$$L_{ER}^{N} = \frac{L_E^{max} - L_{ER}}{L_E^{max} - L_E^{min}} \tag{6}$$

And finally, the normalized depth of the oil reservoir is expressed by:

$$D_{ER}^{N} = \frac{D_R^{max} - D_{ER}}{D_R^{max} - D_R^{min}} \tag{7}$$

Distance and depth can be used as a proxy economic parameter to consider when connecting an emitter to a prospect reservoir. For example, the deeper the reservoir the more investment will be required to achieve the necessary compression capabilities and facility sizing.

Figure 7 summarizes the steps that can be followed using these expressions. For example, we can look for reservoirs that are within 300 km (1) of an emission source (3) in the United States (2). We can investigate the historical emissions trend (4) and identify which reservoirs have the highest potential capacity to store CO_2 (5). The higher the storage capacity the longer the EOR scheme can last. Also, we can compare reservoirs in terms of their distance, potential storage capacity and depth (6). In this way, we can quickly identify the reservoirs that are most likely to be suitable to store CO_2 emissions during an EOR scheme.

Figure 7. Facility emission source analysis: Identifying potential reservoirs to dispose CO_2

Nomenclature

A	*Ratio of potential storage of an oil reservoir with respect to the size of the C02 emitter*
C	*Reservoir capacity*
D	*Depth*
L	*Distance*
M	*Potential Storage*
q	*Annual emission*
W	*Weighting factor*

Superscripts

R	*Reservoir*
N	*Normalized*
max	*Maximum value within a country*
min	*Minimum value within a country*

Subscripts

E	*Emission source*
R	*Reservoir*
ER	*Linked emission source and reservoir*
CO_2	*Carbon dioxide*

Reservoir Analysis

From the reservoir perspective, the normalized factors can be estimated similarly. The difference is that A_{ER} is now used to estimate how long it will take to reach the maximum storage capacity of an oil reservoir.

$$A_{ER} = \frac{M_{CO_2}^{R}}{q_E} \quad (8)$$

$$C_{ER}^{N} = \frac{A_E^{max} - A_{ER}}{A_E^{max} - A_E^{min}} \quad (9)$$

$$L_{ER}^{N} = \frac{L_E^{max} - L_{ER}}{L_E^{max} - L_E^{min}} \quad (10)$$

In this instance, distance and storage potential are the parameters that can be used as economic proxy.

To implement a CO_2-EOR scheme we need to find which emission sources are close to our reservoir and produce enough emissions. Figure 8 summarizes how we can perform a reservoir analysis. Following the proposed calculations, we can find which CO_2 emission sources are within a 300 km (1) radius from our reservoir (3) in the United States (2). We can then explore how these emission sources rank among each other in terms of their distance and how they relate to the reservoir potential storage capacity (4). Also, the average annual emissions (5) and historical trends (6) of each source can be considered in our evaluation.

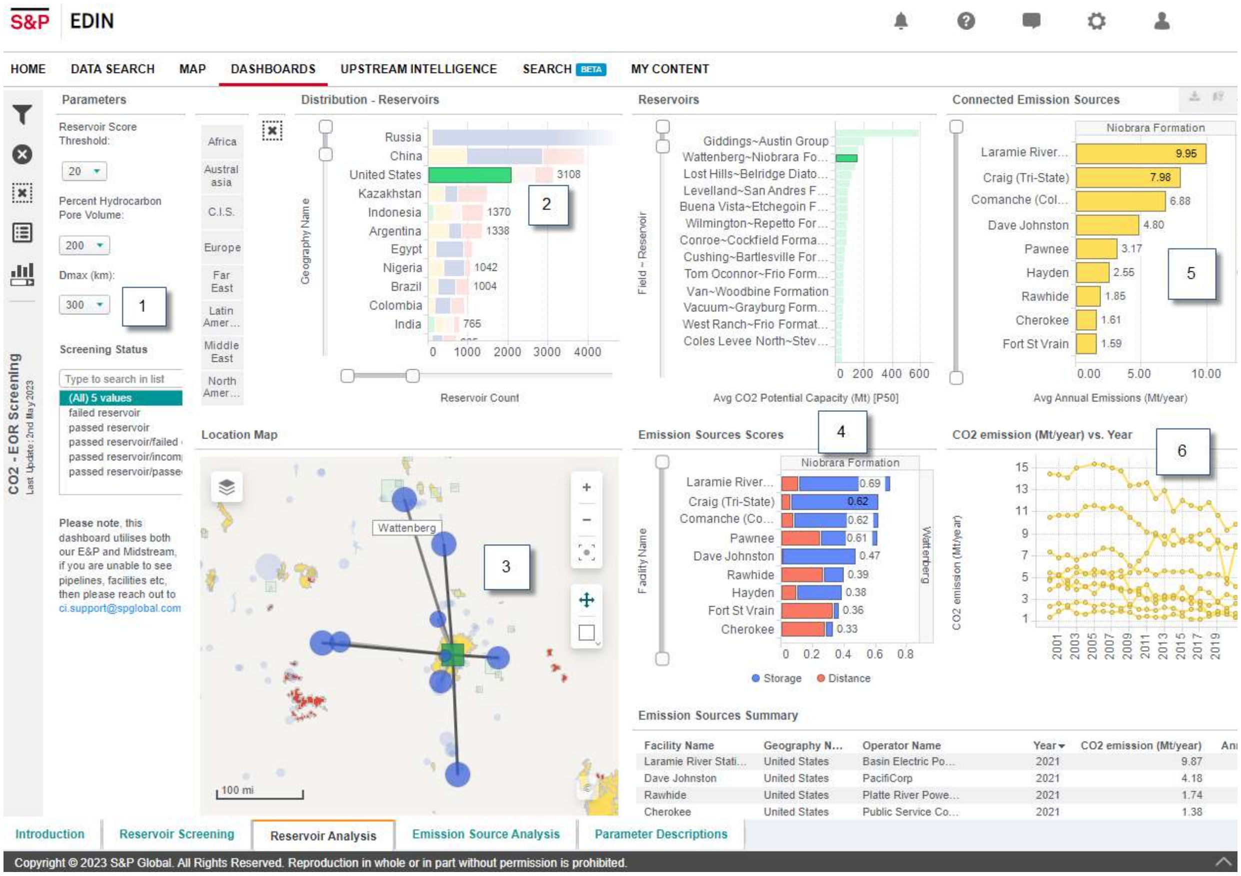

Figure 8. Reservoir analysis: Potential facility emission sources to be used for CO_2 EOR

Nomenclature

A	*Ratio of potential storage of an oil reservoir with respect to the size of the C02 emitter*
C	*Reservoir capacity*
L	*Distance*
M	*Potential storage*
q	*Annual emission*
W	*Weighting factor*

Superscripts

R	*Reservoir*
N	*Normalized*
max	*Maximum value within a country*
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Subscripts

E	*Emission source*
ER	*Linked emission source and reservoir*
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Imputation of missing values

Calculating required parameters (Bachu, 2016)

The following expressions are used to estimate missing reservoir parameters whenever possible.

$$T = 0.0164 \times d + 32 \quad (11)$$

$$p_i = 0.45 \times d \quad (12)$$

$$\text{Initial Pore Pressure Gradient} = \frac{p_i}{d} \quad (13)$$

$$R_s = c_1 \times \gamma_g \times p^{c_2} \times e^{c_3\left(\frac{\gamma_o}{T+460}\right)} \begin{cases} p = p_i \\ \gamma_g = 0.6 \\ \gamma_o \le 30 \Rightarrow c_1, c_2, c_3 = 0.0362, 1.0937, 25.7240 \\ \gamma_o > 30 \Rightarrow c_1, c_2, c_3 = 0.0178, 1.1870, 23.9310 \end{cases} \quad (14)$$

$$\mu_{od} = \frac{3.141 \times 10^{10}}{T^{3.444}} [\log(\gamma_o)]^{10.313 \times \log(T) - 36.447} \quad (15)$$

$$\mu_{ob} = A(\mu_{od})^B$$
$$A = 10.715 \times (R_s + 100)^{-0.515} \quad (16)$$
$$B = 5.44 \times (R_s + 150)^{-0.338}$$

$$MMP = -329.558 + (33056.106 \times \gamma_o^{-0.87} \times 1.005^T) - 18724.806 \times \gamma_o^{-0.87} \quad (17)$$

$$S_{oi} = 100 - S_{wi} \quad (18)$$

$$\text{Initial Pore Space Oil Saturation} = 10^{-4} \times S_{oi} \times \phi \quad (19)$$

$$\text{Remaining Oil Fraction in the Reservoir (\%)} = 100 - \text{Oil Recovery Factor} \quad (20)$$

$$\text{Remaining Oil in the Reservoir (MMstb)} = 0.01 \times \text{ Remaining Oil Fraction in the Reservoir (\%)} \times OOIP \quad (21)$$

where:

T	*Temperature, ºF*
d	*Depth, ft*
p_i	*Initial Reservoir Pressure, psi*
γ_o	*API Gravity*
γ_g	*Gas Specific Gravity*
R_s	*Solution Gas Oil Ratio, scf/stb*
μ_{od}	*Dead Oil Viscosity, cp*
μ_{ob}	*Live Oil Viscosity, cp*
MMP	*Minimum Miscibility Pressure, psi*
S_{wi}	*Initial Water Saturation, %*
S_{oi}	*Initial Oil Saturation, %*
ϕ	*Porosity, %*
$OOIP$	*Original Oil in Place, MMstb*

References

Bachu, Stefan: "Identification of oil reservoirs suitable for CO2-EOR and CO2 storage (CCUS) using reserves databases, with application to Alberta, Canada.", *International Journal of Greenhouse Gas Control* 44 (2016), 152-165.

Azzolina, N.A., Nackles, D.V., Gorecki, C.D., Peck, W.D., Ayash, S.C., Melzer, S.L.,Chatterjee, S.: “CO2 storage associated with CO2 enhanced oil recovery: a statistical analysis of historical operations.”, *International Journal of Greenhouse Gas Control* 37 (2015), 384–397.

Angarita, Edgar Eduardo Yáñez, et al.: "Rapid screening and probabilistic estimation of the potential for CO2-EOR and associated geological CO2 storage in Colombian petroleum basins.", *Petroleum Geoscience* 28.1 (2022), petgeo2020-110.