MILESTONE REPORT: RESERVOIR MASS ACCOUNTING METHODOLOGY

"Carbon Life Cycle Analysis of CO_2-EOR for Net Carbon Negative Oil (NCNO) Classification"

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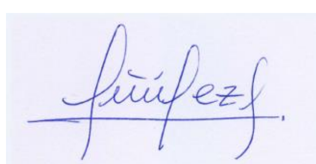
Submitting Official: Vanessa Nunez-Lopez, PI:	

Introduction

In the context of monitoring carbon for geologic storage, the target of the monitoring strategy is the purchased CO_2, not the total volumes/mass of CO_2 injected into the oil reservoir for enhanced oil recovery (EOR), which include recycle gas. Similarly, the target of our reservoir mass accounting methodology is the mass of purchased CO_2. In fact, the overall amount of CO_2 stored in the reservoir during the EOR flood is approximately the amount of CO_2 delivered to the EOR site for injection.

In this sense, our preferred methodology differs from most current methodologies in that we recommend not to account for recycle gas, as it introduces significant complexities which lead to significant mass accounting errors. Another difference is that we do propose accounting for CO_2 subsurface losses, both laterally and vertically outside of a pre-established subsurface volume. The latter is in agreement, however, with the current working draft of the International Organization for Standardization (ISO 265).

We also developed an alternative methodology to our preferred one, because existing local regulations, contractual structures, financial expectations, etc., might require that the EOR operator report recycle mass accounting. Both methodologies include losses of CO_2 at the surface, which correspond to CO_2 releases from surface equipment during a number of identified expected and unexpected events. We received valuable input and review from Hilcorp and the Petra Nova team on practical aspects of EOR operations that were necessary in the development of the methodologies.

Finally, we mention the importance of including an account for indirect CO_2 emissions, which correspond to the CO_2 equivalent emissions associated with the electricity consumption of equipment and processes at the EOR site.

1. Reservoir Mass Accounting Methodology (preferred method)

All CCUS projects sponsored by the DOE regional sequestration partnership are required to report the volumes/mass of carbon geologically stored through the process of CO_2 EOR. These projects report their mass accounting similarly: total injected CO_2 minus total produced/recycle CO_2. SECARB's Early Project at Cranfield, for example, used equation (1) below, which corrects for methane concentration both in the purchased CO_2 and in the produced gases. Most of these projects, including Cranfield, did/do not include CO_2 losses in the subsurface or in the surface.

Net CO_2 Stored = (Total CO_2 Injection – Average CH_4 in Injection Stream) – (Total CO_2 Produced – Average CH_4 in Production/Recycle Stream) (eq. 1)

EPA's greenhouse gas reporting program Subpart RR §98.442, however, does require the accounting of CO_2 leakages at the surface (see eq. 2, corresponding to eq. RR-11 in subpart RR), and makes the distinction between surface CO_2 leakage (through the surface interface) and CO_2 equipment leakage (as described in table 2)

$$CO2_{sequestered} = CO2_{injected} - CO2_{produced} - CO2_{surf\ leakage} - CO2_{equip\ leakage*} \quad \text{(eq. 2)}$$

Our methodology differs from the mentioned methodologies in that it follows purchased CO_2 as the key mass accounting parameter -instead of total injected CO_2- in order to avoid the accounting of recycle gas, as it introduces significant complexities which lead to significant mass accounting errors. Our rational is in agreement, however, with the current working draft of the International Organization for Standardization (ISO 265).

One of the issues associated with CO_2 recycle accounting include cumulative errors that arise from the use of a larger number of measuring equipment. Based on EOR operator experience (verbal communication), the sum of CO_2 injection volumes from wellhead flow meters does not conform exactly to the total volume of purchased CO_2. This inconsistency not only comes from equipment errors in CO_2 volume calculations that are intrinsic to the flow meters used in oil and gas operations but also from equipment calibration issues.

In the case of commonly used mass flow meters -such as Coriolis flow meters-, which measure mass per unit of time, knowledge of the fluid density is required for the calculation of an accurate volumetric flow rate. The mass is simply divided by density to calculate the volumetric flow rate. However, in the case of a CO_2 recycling stream with varying density, this relationship is not simple and results in errors in the order of a couple percentage points. In addition to calculation errors, equipment calibration is frequently needed as it is affected by changes in the vibration of the flow lines through which the fluids flow.

Another complexity of recycle mass accounting is introduced in CO_2 EOR operations, such as Cranfield, where the CO_2 is not separated from the produced gases before reinjection. The concentration of produced hydrocarbon gases, most commonly methane, in the recycling stream increases with time as more gases are stripped out of the oil. In this case, gas analysis is required at the time of measuring.

We propose the use of equation 3 as the basis and preferred method of our reservoir mass accounting methodology, as it results in a more direct and accurate mass accounting protocol.

$$M_{stored} = M_{purchased} - M_{lost\ subsurface} - M_{lost\ surface} \qquad \text{(Eq. 3)}$$

where,

M_{stored} = mass of CO_2, in metric tons, geologically stored in the reservoir through CO_2 EOR during x reporting period. It equals the mass of CO_2 purchased minus subsurface and surface CO_2 losses. If there aren't losses, the mass of CO_2 stored/retained in the subsurface should simply equal the mass of CO_2 purchased.

$M_{purchased}$ = mass of CO_2, in metric tons, delivered to the EOR site from the CO_2 capture facility, measured at the transfer meter during x reporting period, see "M_1" location in figure 2. Any CO_2 impurities in the purchased stream need to be subtracted using the CO_2 purity provided by the CO_2 capture facility. A measurement error needs to be included. The meter used could be a mass flow meter or a volumetric flow meter. Please refer to the recommended flow meter equation in the Appendix.

$M_{lost\ subsurface}$ = mass of CO_2, in metric tons, that migrated outside of a subsurface volume (see fig. 1), which has been previously defined by a monitoring, verification, and accounting (MVA) program. The subsurface volume is the volume within the oil field lease boundary, above the base of deepest EOR producing Formation, and below the base of an *above zone monitoring interval* (AZMI)*. This subsurface volume may include some zones in conventional oil/gas production. If CO_2 should migrate out of the CO_2 injection zone and reach other producing zones, the EOR operator should quantify CO_2 losses via production testing of all actively producing zones. These losses should be reported quarterly.

Similarly, if CO_2 should migrate laterally outside of the EOR lease boundary, this loss should be quantified. An MVA program should provide this information during the operation. Reservoir modeling can be used pre CO_2 injection for the estimation of these potential losses. Lateral migration of CO_2 is considered a loss because CO_2 that flows into a neighboring lease might get produced in adjacent operations. These losses should be reported quarterly.

*AZMI is a laterally continuous, thin, subsurface layer that lies above the CO_2 injection zone. This interval needs to be carefully selected to monitor vertical CO_2 migration as part of an MVA program. AZMIs should satisfy specific petrophysical conditions needed for CO_2 leakage detection assurance.

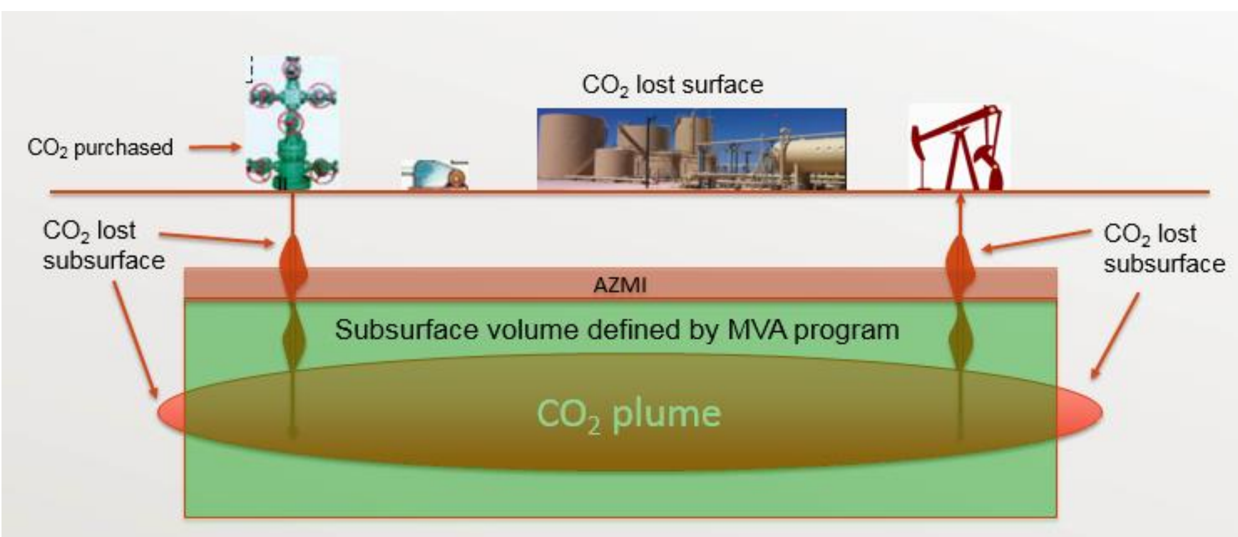


Fig. 1. Elements of reservoir mass accounting

$M_{lost\ surface}$ = mass of CO_2, in metric tons, lost at the surface. These losses include any potential leakage from surface equipment, which for the purpose of this methodology include (see "M_5" locations in fig. 2):

(1) Blowdown valve releases: a safety release of gas accumulated in equipment, such as the recycle gas compressors. These are low frequency events. We recommend that the number of these events be assessed during the first year of operation in order to determine the significance of the CO_2 volumes released.

(2) Maintenance releases: any CO_2 release during maintenance operations, including releases to depressurize equipment for safety reasons.

(3) Troubleshooting releases: any CO_2 release during troubleshooting operations, including repair of faulty electrical systems, equipment leaks, etc.

(4) Venting: A potentially continuous release at the EOR site. Fugitive emissions should be allocated under this category. A vapor recovery unit (VR) could be used to estimate vented/fugitive emissions.

(5) Unusual events: any CO_2 release from pipelines and wells, including blowouts, workovers, leaks.

(6) Flare releases: Another potentially continuous release of CO_2 at the flare. It is a type of venting located after the extra low-pressure equipment. A vapor recovery unit (VR) could be used to estimate vented/fugitive emissions.

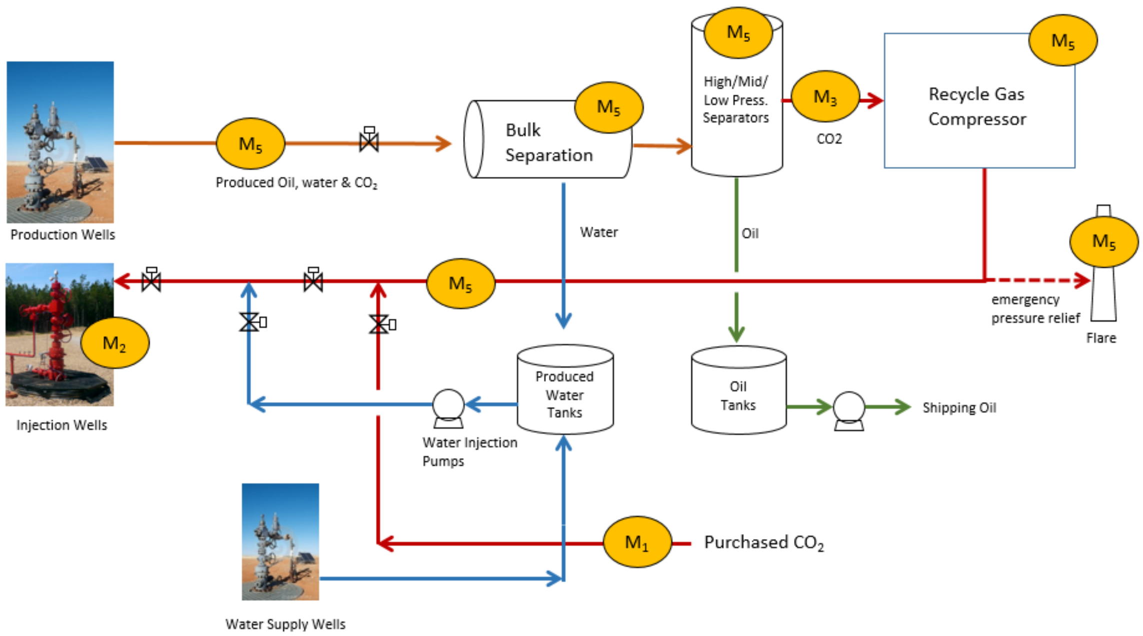


Fig. 2. Surface mass accounting monitoring locations. The subscript number in $M_{\#}$ represents the mass accounting element # in Table 1.

2. Reservoir Mass Accounting Methodology (with recycle gas accounting)

The role of recycling has been widely misunderstood in CCUS. Many reputable accounting methods use a traditional petroleum engineering method that is based on pore volumes swept based on a total mass injected, which is the sum of all the CO_2 injected. As the project matures the total CO_2 injected will include new CO_2 from the capture plant plus recycled CO_2.

As it was explained in the previous section, accounting for recycle CO_2 is a complex task, which results in inaccuracies. However, existing local regulations, contractual structures, financial expectations, etc., might require that the EOR operator report recycle mass accounting. If this is the case, we recommend the use of equation 4.

$$M_{stored} = M_{total\ injected} - M_{recycle} - M_{lost\ subsurface} - M_{lost\ surface} \quad \text{(Eq. 4)}$$

Where,

$M_{total\ injected}$ = total mass of CO_2, in metric tons, injected into the reservoir during x reporting period. If the EOR operation is inclusive of a CO_2 separation facility, where the CO_2 is separated from produced reservoir gases, then the cumulative mass of CO_2 injected will be the sum of all the CO_2 injected, which as the project matures will include new CO_2 from the capture plant (purchased CO_2) plus recycled CO_2.

$M_{recycle}$ = Mass of CO_2, in metric tons, produced from the reservoir, separated, processed, compressed, and reinjected into the reservoir during x reporting period. If the CO_2 produced from the reservoir is not separated from other produced hydrocarbon gases, as it is commonly the case in Gulf Coast CO_2 floods, the mass of CO_2 recycled needs to be corrected for the continuous increase in the concentration of impurities in the CO_2 injection stream. This concentration increases with every new injection cycle, as more hydrocarbon gases get produced along with the oil and the CO_2. In this case, the operator needs to establish and implement gas analysis procedures that measure the concentration of these impurities (mostly CH_4) in the recycle stream at the time of reporting.

For increased accuracy, the total injected CO_2 mass should be the sum of the purchased CO_2 mass -measured by a flow meter at the transfer location- plus the CO_2 recycle mass measured by a flow meter located upstream of the recycle gas (RC) compressor/s, see "M_3" location in fig. 2. The purchased CO_2 mass also needs to be corrected by the CO_2 concentration at the measuring locations. Therefore, a gas analysis is required at the time of reporting.

We do not recommend the estimation of the total CO_2 injection mass as the sum of the CO_2 injection mass of individual injection wells. However, wellhead flow meters at CO_2 injection wells are still needed for allocation purposes.

There are two reasons for this recommendation, (1) having less measuring points decreases flow meter errors and prevents inconsistencies, and (2) the highest quality meters are the ones located upstream of the recycle gas compressor/s. Note that even these higher quality meters (i.e. V-cone flow meter), which are differential pressure meters, produce errors of +/- 0.5% according to manufacturers, and errors as large as +/- 1 % according to operators (personal communication). Please refer to the recommended flow meter equation in the Appendix.

Table 1 lists the all the parameters needed in the use of equations 3 and 4 and their proposed reporting frequency. Table 2 compares the parameters required in our proposed mass accounting methodology with the parameters required in Subparts RR and UU of EPA's greenhouse gas reporting program §98.442.

Included in the Appendix are our proposed reporting tables (3 to 8) for components related to mass of CO_2 lost at the surface, as well as a table (9) for components related to CO_2 recycle mass and CO_2 purchase mass.

Table 1. Mass accounting parameter and frequency of reporting.

<table>
<tr><th>#</th><th colspan="2">Proposed Mass Accounting Parameter</th><th>Frequency</th></tr>
<tr><td>1</td><td colspan="2">Mass of CO_2 purchased</td><td>Quarterly</td></tr>
<tr><td>2</td><td colspan="2">Mass of CO_2 injected*</td><td>Quarterly</td></tr>
<tr><td>3</td><td colspan="2">Mass of CO_2 recycled*</td><td>Quarterly</td></tr>
<tr><td>4</td><td colspan="2">Mass of CO_2 lost in the subsurface</td><td>Quarterly</td></tr>
<tr><td rowspan="6">5</td><td rowspan="6">Mass of CO_2 lost in the surface</td><td>Blowdown releases</td><td>Assess during 1st year to establish significance</td></tr>
<tr><td>Maintenance releases</td><td>Record date of event</td></tr>
<tr><td>Troubleshooting releases</td><td>Record date of event</td></tr>
<tr><td>Venting</td><td>Quarterly</td></tr>
<tr><td>Unusual events (pipeline releases, well releases: blowouts, workovers, leaks)</td><td>Record date of event</td></tr>
<tr><td>Flare releases</td><td>Quarterly</td></tr>
<tr><td>6</td><td colspan="2">Mass of CO_2 geologically stored</td><td>Quarterly</td></tr>
</table>

***** Required if equation 4 is used.

Table 2: Comparison of required mass accounting parameters

GHGs to be reported	Subpart RR	Subpart UU	Our proposed reporting
Mass of CO_2 received	✓	✓	✓
Mas of CO_2 injected into the subsurface	✓		✓*
Mass of CO_2 produced	✓		
Mass of CO_2 emitted by surface leakage	✓		
Mass of CO_2 equipment leakage and vented CO_2 emissions from surface equipment located between the injection flow meter and the injection wellhead	✓		✓
Mass of CO_2 equipment leakage and vented CO_2 emissions from surface equipment located between the production flow meter and the production wellhead	✓		✓
Mass of CO_2 sequestered in subsurface geologic formations	✓		✓
Cumulative mass of CO_2 reported as sequestered in subsurface geologic formations in all years since the facility became subject to reporting requirements under subpart RR	✓		
Mass of CO_2 recycle			✓*

***** In the case equation 4 is used.

3. Indirect carbon emission accounting at the EOR site

Outside the boundaries of the reservoir mass accounting, the carbon mass balance at the EOR site, or within the gate-to-gate system, should include an account of indirect CO_2 emissions, which correspond to the CO_2 equivalent emissions associated with the electricity consumption of equipment and processes at the EOR site. The methodology for the estimation of these indirect CO_2 emissions is outside of the scope of this report. However, we have included a diagram (fig. 3), which shows the energy intensive locations where indirect CO_2 emissions should be accounted for. The figure is presented as a decision diagram as to cover most common EOR site design configurations. Our estimated Cranfield indirect CO_2 emissions associated with CO_2 injection and general production are presented in figure 4.

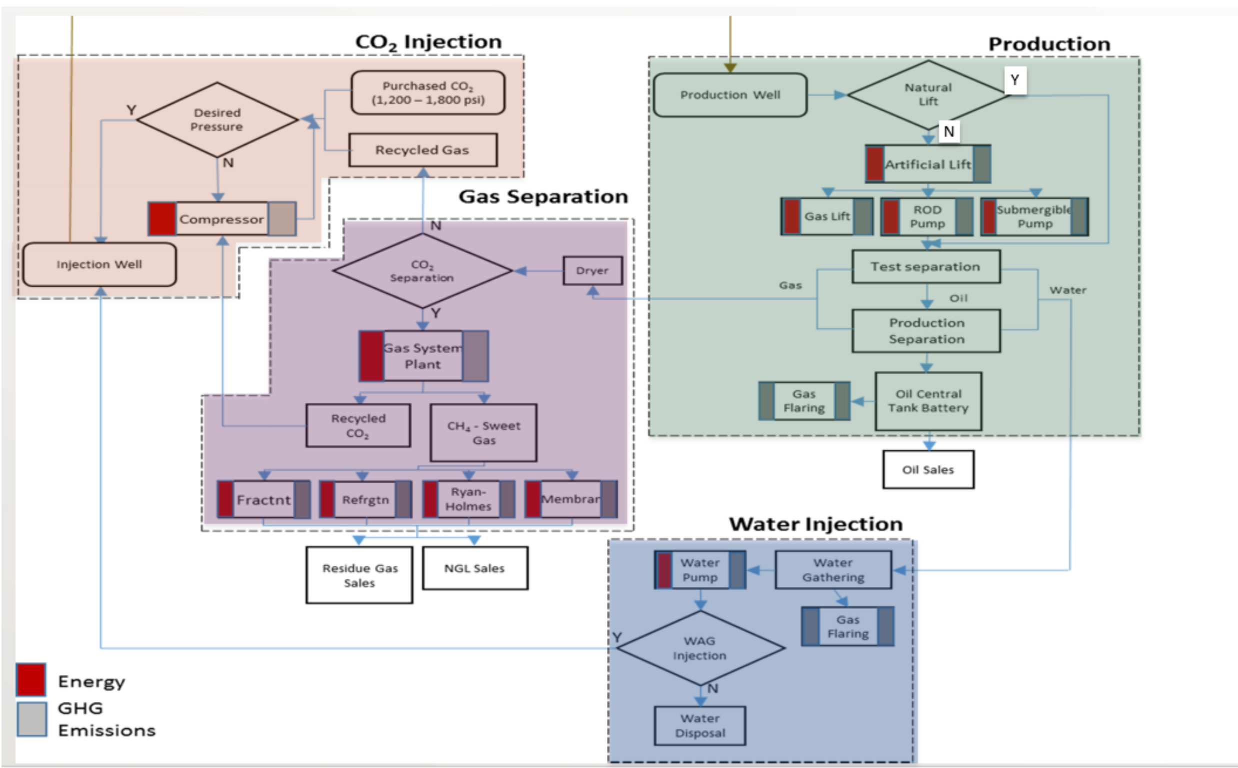


Figure 3. Energy demanding locations that produce indirect carbon emissions

In fig. 4, the average water cut represents 86% of the total liquid production, with an average crude oil production of 949 bbl/D and an average water production of 4,528 bbl/D.

Fig. 5 shows an average CO_2 production of 19,691 Mscf/D with an average grow rate of 14%. Figs. 6 and 7 show the electric intensity and consequent greenhouse gas emissions associated with the CO_2 injection (CO_2 compression) and the artificial lift (gas lift) used to start oil production during the first 3 months of each producing well. Finally, fig. 8 shows our estimates of CO_2 storage at Cranfield in comparison with the cumulative indirect emissions at the EOR site and the cumulative CO_2 emissions associated with the burning of the gasoline (grave) as the refined product of the oil produced at the EOR site. Approximately 40% of the carbon retained in the reservoir is emitted at the grave and about 4% is emitted indirectly at the EOR site. Results indicate that at Cranfield, a continuous direct CO_2 flood (no water alternating gas, WAG), the oil produced can be classified as net carbon negative oil if the system boundary is gate to grave. This confirms that a direct CO_2 injection scenario is conducive to an NCNO classification.

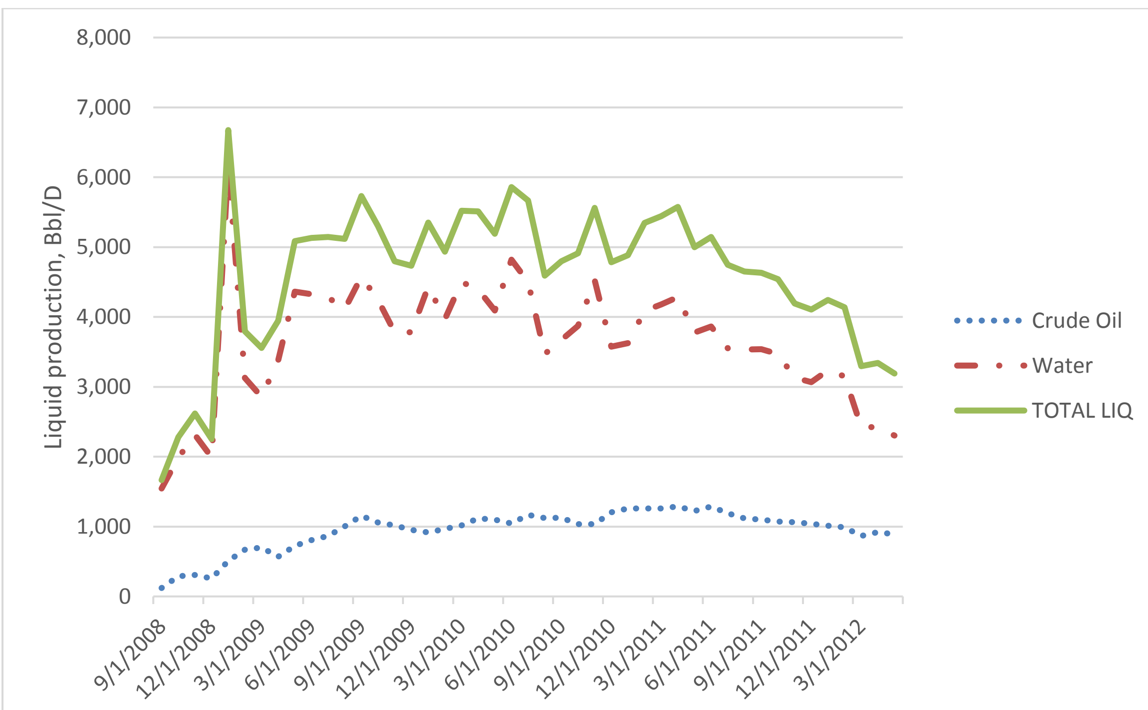


Fig. 4. Cranfield liquid production. Data from the Mississippi oil and gas board.

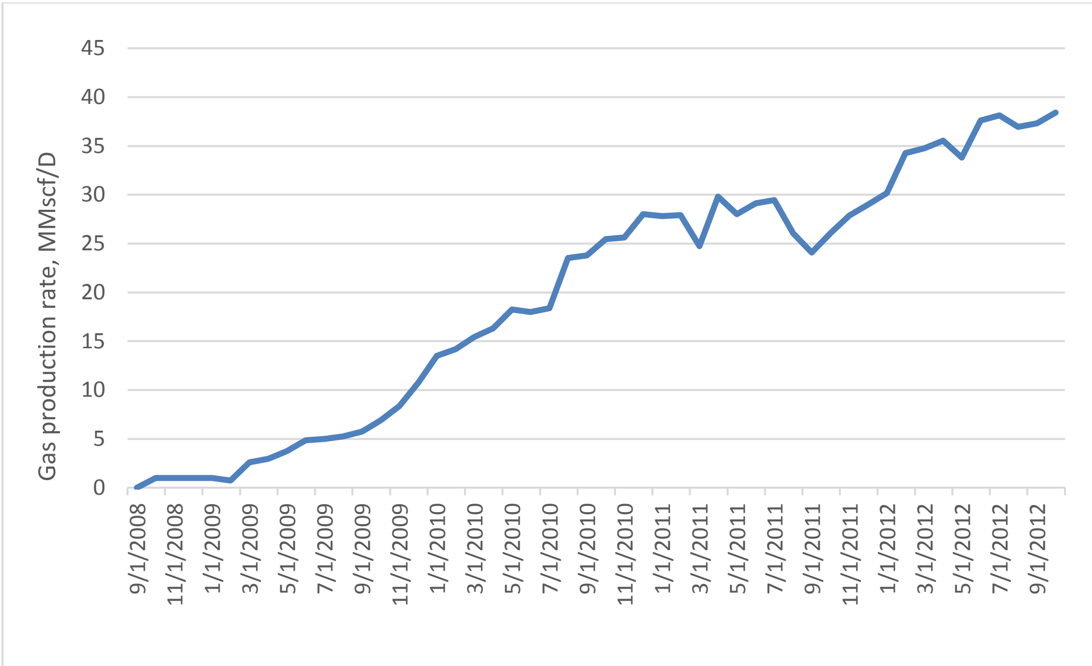


Fig. 5. Cranfield CO_2 production rate. Data from the Mississippi oil and gas board.

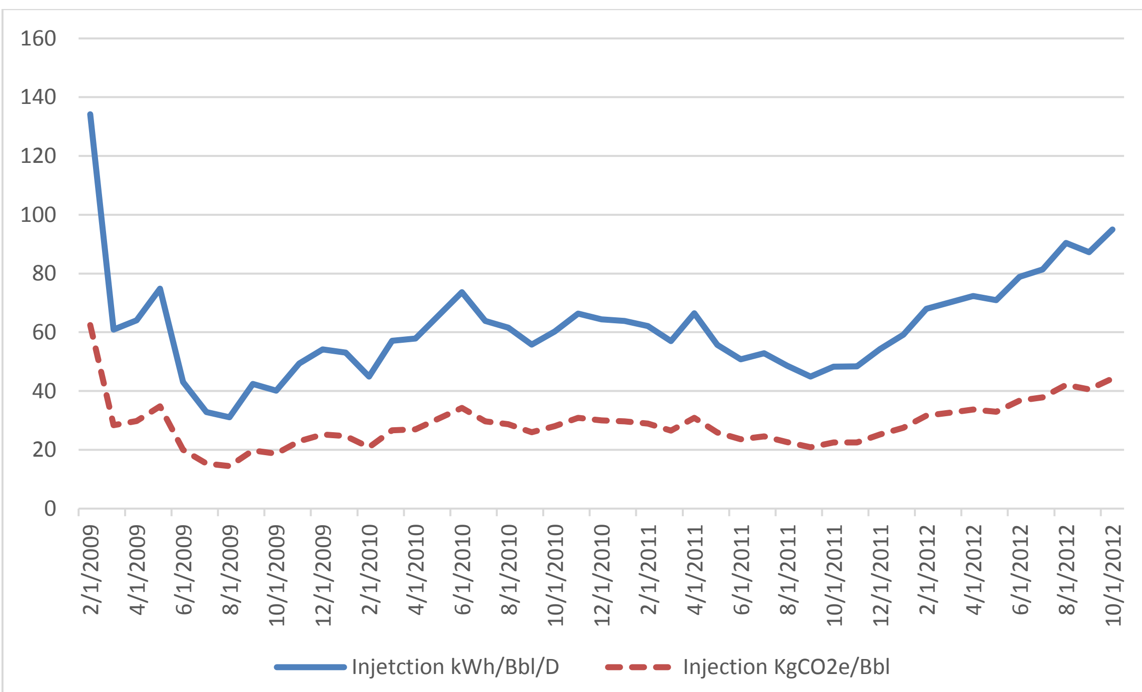


Fig. 6. Cranfield Gas Injection Electric Intensity and GHG Emissions

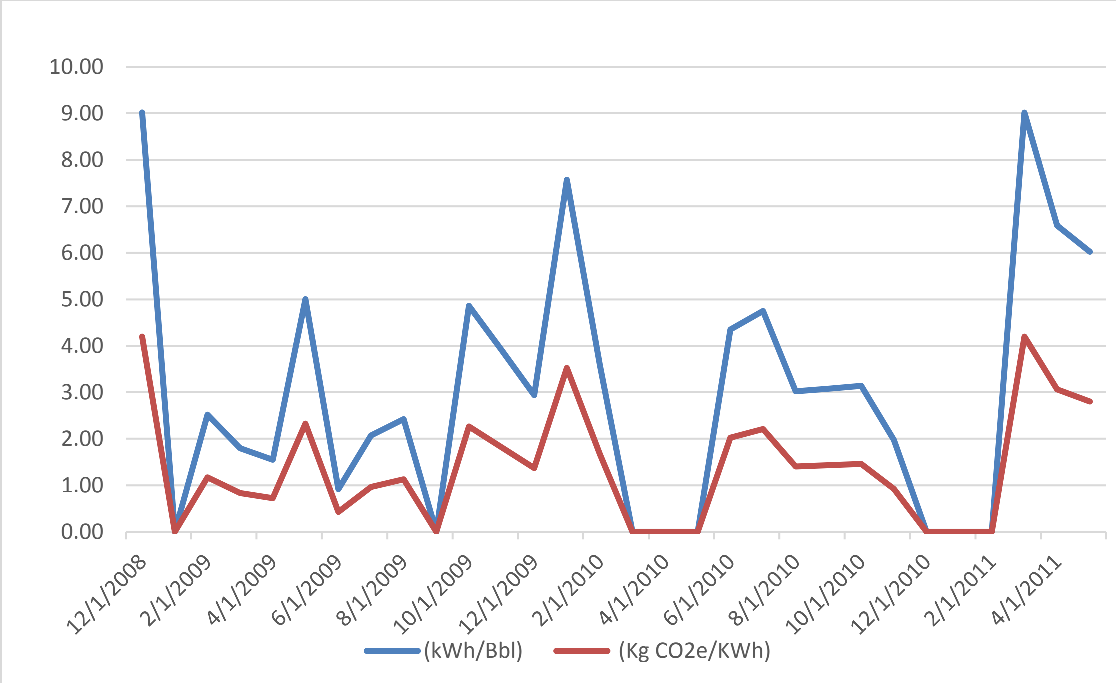


Fig. 7. Cranfield estimated gas lifting electric intensity and GHG Emissions

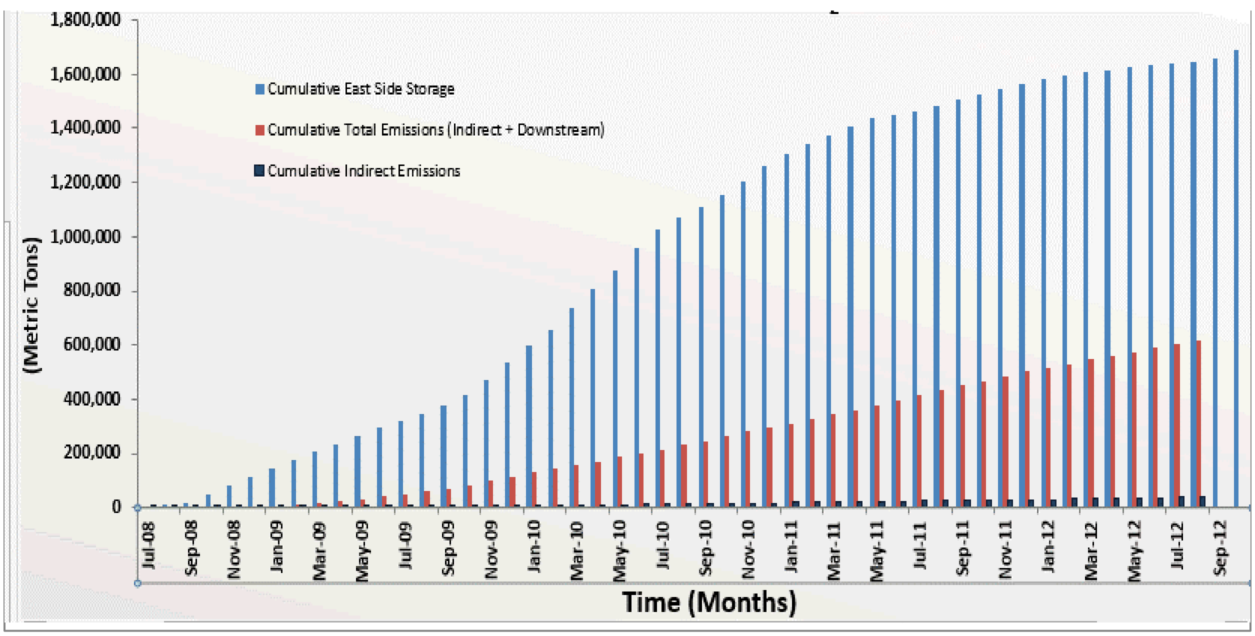


Figure 8. Estimated Cranfield CO_2 storage, indirect emissions of CO_2 equivalent at the EOR site, and downstream emissions from the burning of refined gasoline.

APPENDIX

Flow meter equations

Similar to the equations included in Subpart RR, the amount of CO_2 at a flow meter should be calculated as:

Mass flow meter

$$CO_{2X,fm} = \sum_{Q=1}^{4} q_{fm,Q} * C_{CO_2,fm,Q}$$

Volumetric flow meter

$$CO_{2X,fm} = \sum_{Q=1}^{4} V_{fm,Q} * D * C_{CO_2,fm,Q}$$

Where,

$CO_{2X,\ fm}$ = mass of CO_2, in metric tons, measured through flow meter “fm” during X reporting period. X could be annual, the total time of CO_2 injection, or any required reporting time.

$q_{fm,\ Q}$ = mass of CO_2, in metric tons, measured through flow meter “fm” during quarter “Q”.

$C_{CO2,\ fm,\ Q}$ = concentration of CO_2 at flow meter “fm” from gas analysis at the time of reporting quarter “Q”.

$V_{fm,\ Q}$ = volume of CO_2, in standard cubic meters, through flow meter “fm” during quarter “Q”.

D = density of CO_2 in metric tons per cubic meter (0.0018682)

Tables for components related to mass of CO_2 lost at the surface

Table 3: Blowdown releases (assess frequency during 1st year to assess significance)

Date of event	Location of release	Measuring/estimation method	Type of data acquired	Conversion	CO_2 mass	Uncertainty
	Recycle gas compressor					
	Flash gas compressor					

Table 4: Maintenance releases

Date of event	Location of release	Measuring/estimation method	Type of data acquired	Conversion	CO_2 mass	Uncertainty

Table 5: Troubleshooting releases

Date of event	Location of release	Measuring/estimation method	Type of data acquired	Conversion	CO_2 mass	Uncertainty

Table 6: Venting releases

Date of event	Location of release	Measuring/estimation method	Type of data acquired	Conversion	CO_2 mass	Uncertainty

Table 7: Unusual events (release from pipelines; release from wells: blowout, workover, leaks)

Date of event	Type of event	Measuring/estimation method	Type of data acquired	Conversion	CO_2 mass	Uncertainty

Table 8: CO_2 at Flare (Method to be determined after CO_2 recycling starts)

Date of measurement	Acquiring method	Type of data acquired	Conversion	CO_2 mass	Uncertainty

Table for components related to CO_2 recycle mass and CO_2 purchase mass

Table 9: Mass of CO_2 recycle and CO_2 purchase

	Measurement locations	Date, monthly	% CO_2	CO_2 mass	Uncertainty
CO_2 Recycle	Meter upstream of Recycle Gas Compressor				
Purchased CO_2	CCS capture				