Supporting Information

Carbon footprint of oil produced through Enhanced Oil Recovery using carbon dioxide directly captured from air

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This PDF file includes:

Supporting Information Text

Data from existing CO_2-EOR projects. Figure 5 presents the data on reservoir exploitation for 16 CO_2-EOR projects that has been reported by Azzolina et al. (1). The study developed models fitted to the field data for each project, providing key values:

- The net CO_2 utilization, U_{CO_2}, defined as the mass of CO_2 stored per unit mass of oil produced.
- The cumulative incremental oil recovery, R_{EOR}, expressed as % of the original oil in place (OOIP), and defined as the additional oil produced due to CO_2 injection.
- The CO_2 retention, defined as the fraction of injected CO_2 retained in the reservoir.

The net CO_2 utilization and the CO_2 retention are average (i.e., cumulative) values calculated from the start of the EOR operation up to a specific point in time during the operation. Fig. S1 illustrates the evolution of these values as a function of the total cumulative injected volume of CO_2 and H_2O, expressed as a percentage of the hydrocarbon pore volume (HCPV). The EOR operation progresses over time as the injected volume increases. Based on these parameters, the fraction of carbon emitted relative to stored, ξ, is computed using Equation 6 (the reader is referred to the main text for the nomenclature):

$$\xi = \frac{V_{CO_2}^{\mathrm{target}}}{V_{\mathrm{CO_2}}^{\mathrm{stored}}} = \frac{1}{\eta_{\mathrm{CO_2}}} \frac{M_{\mathrm{CO_2}}}{M_o} \left(\frac{1}{U_{\mathrm{CO_2}}} \frac{R_{\mathrm{TOT}}}{R_{\mathrm{EOR}}} \right) \quad [1]$$

Here, the term in parentheses represents the real net CO_2 utilization. If oil produced before EOR is ignored, then $R_{\mathrm{TOT}} = R_{\mathrm{EOR}}$, and the climate impact is denoted as ξ_{EOR}. Otherwise, $R_{\mathrm{TOT}} = R_{\mathrm{EOR}} + R_{\mathrm{PRE}}$, where R_{PRE} denotes the oil recovered before EOR. A value of 35 % OOIP was assumed for R_{PRE} (2), and the climate impact is referred to as ξ_{TOT}. Table S1 summarizes the operating variables and the calculated ξ_{EOR} and ξ_{TOT} for CO_2-EOR projects from various studies. For data from Ref. (1), the field data at the end of operation, i.e., at the maximum injected volume, were utilized.

Carbon footprint of produced oil. Using data from Azzolina et al. (1) and Equation 1, we can estimate the average carbon footprint of the produced oil, C_{oil}, in tons of CO_2 emitted per ton of oil used, as follows:

$$C_{\mathrm{oil}} = \frac{M_{\mathrm{CO_2}}}{M_o} - \eta_{\mathrm{CO_2}}\, U_{\mathrm{CO_2}} \frac{R_{\mathrm{EOR}}}{R_{\mathrm{TOT}}} \quad [2]$$

Fig. S2 illustrates the carbon footprint of the produced oil as a function of the oil recovered before EOR, R_{PRE}, namely during the primary and secondary production phases, for $\eta_{\mathrm{CO2}} = 0.85$. In the United States, where the CO_2-EOR projects were conducted, most oil reservoirs recover 25 to 49 % OOIP before EOR (2), as shown by the grey area in Fig. S2. For these recovery rates, most CO_2-EOR projects would have produced oil with a carbon footprint ranging from 2.1 to 2.8 t of CO_2 per ton of oil, if the stored CO_2 had been captured from the air. Consequently, DAC-based CO_2 EOR reduced the carbon footprint of oil by 10 to 32 %. However, all projects produced carbon-positive oil when the oil recovered before EOR exceeded only 5 % OOIP, highlighting the unfeasibility of achieving carbon-neutral oil within the reservoir's boundaries.

References

1. NA Azzolina, et al., CO_2 storage associated with CO_2 enhanced oil recovery: A statistical analysis of historical operations. *Int. J. Greenh. Gas Control.* **37**, 384–397 (2015).
2. L Lake, R Johns, B Rossen, G Pope, *Fundamentals of Enhanced Oil Recovery.* (Society of Petroleum Engineers), (2014).
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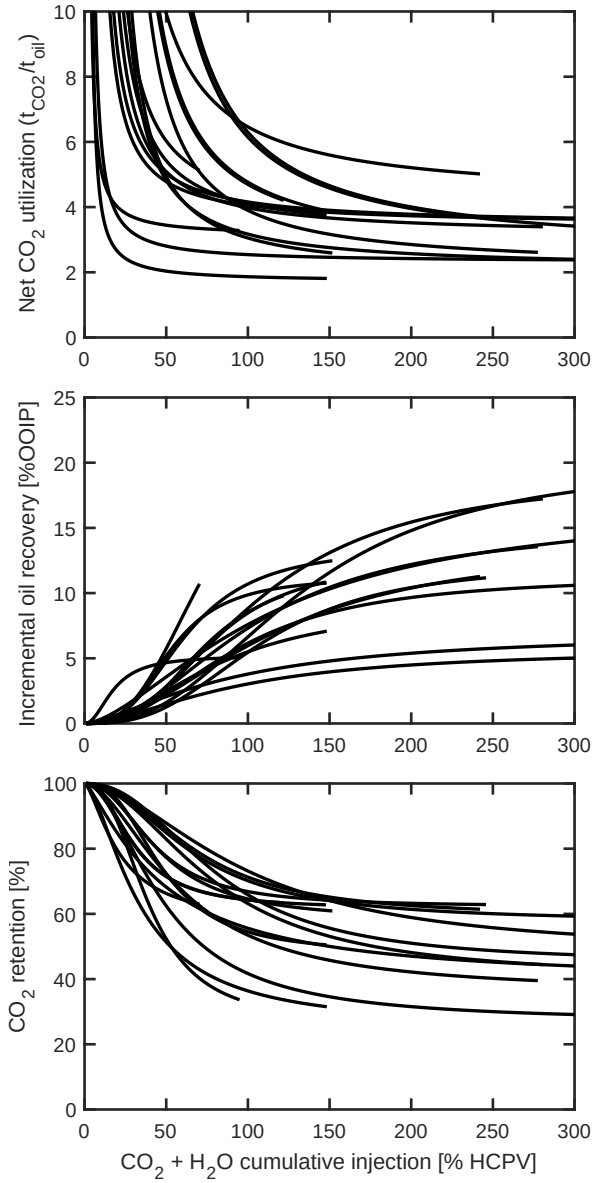

Fig. S1. Evolution of the net CO_2 utilization (top), the incremental oil recovery (middle), and the CO_2 retention (bottom), as a function of the cumulative volume of injected CO_2 and H_2O, expressed as a percentage of the hydrocarbon pore volume (HCPV). Each line represents one of the 16 CO_2-EOR projects reported in Ref. (1).

Table S1. Data for CO_2-EOR projects used to generate Figure 3 and Figure 5 in the manuscript. Taken from Table 1 in Ref. (1), Table 1 in Ref. (3), and Table 1 in Ref. (4). The value ξ_{TOT} can not be computed for datasets missing an oil recovery value.

Project name (ref.)	Injected volume[1] (% HCPV)	Oil recovery[2] (% OOIP)	Net CO_2 utilization (t_{CO_2}/t_{oil})	ξ_{EOR} (–)	ξ_{TOT} (–)
Site A (1)	246	9.7	11.2	1.0	4.2
Site B (1)	281	8.9	17.2	1.1	3.3
Site C (1)	148	10.2	10.8	1.0	4.0
Site D (1)	450	8.1	19.2	1.2	3.4
Site E (1)	242	13.2	11.3	0.7	3.0
Site F (1)	302	9.6	10.6	1.0	4.3
Site G (1)	148	4.8	7.1	2.0	12.1
Site H (1)	152	6.8	12.5	1.4	5.4
Site I (1)	478	6.0	6.5	1.6	10.4
Site J (1)	70	13.5	10.7	0.7	3.1
Site K (1)	650	9.3	5.5	1.0	7.7
Site L (1)	122	11.0	9.8	0.9	4.0
Site M (1)	95	8.6	5.0	1.1	8.9
Site N (1)	148	9.9	10.8	1.0	4.2
Site R (1)	378	6.2	14.8	1.6	5.3
Site W (1)	278	6.9	13.6	1.4	5.1
Southwest USA average (3)	N/A	N/A	10.0	1.0	N/A
Northwest USA average (3)	N/A	N/A	8.0	1.2	N/A
Oklahoma average (3)	N/A	N/A	7.5	1.3	N/A
Southeast USA average (3)	N/A	N/A	13.3	0.7	N/A
Garber (4)	35	14	6.0	1.6	5.7
Little Creek (4)	160	21	12.6	0.8	2.1
Maljamar (4)	30	8.2	10.7	0.9	4.8
Maljamar (4)	17	0.7	6.1	1.6	N/A
Slaughter Estate (4)	26	20	3.7	2.6	7.2
Weeks Island (4)	24	8.7	3.3	2.9	14.8

[1] Injected fluids include CO_2 and H_2O, and HCPV refers to the to the hydrocarbon pore volume. [2] Oil recovered during CO_2-EOR only, and OOIP refers to the original oil in place.

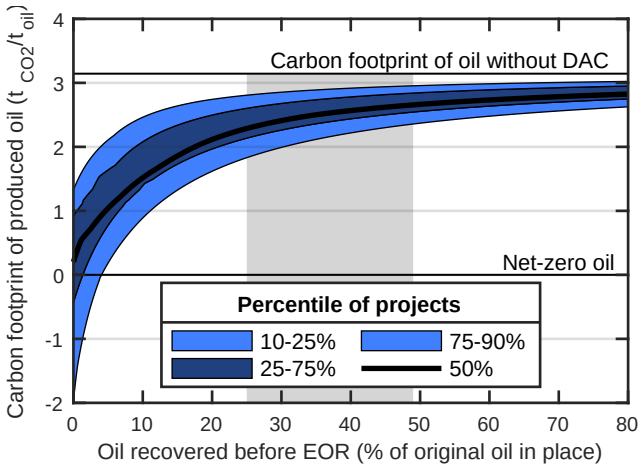

Fig. S2. Carbon footprint of the oil produced, C_{oil}, as a function of oil recovered before EOR, R_{PRE}, for 16 CO_2-EOR projects reported in Ref. (1). The black line is the median, the dark blue area indicates the interquartile range (25$^{\mathrm{th}}$ to 75$^{\mathrm{th}}$ percentiles), and the light blue areas show the 10$^{\mathrm{th}}$ to 25$^{\mathrm{th}}$ and 75$^{\mathrm{th}}$ to 90$^{\mathrm{th}}$ percentiles. The grey area represents a typical range of oil produced before EOR for reservoirs in the US (2).