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Putting the genie back in the bottle: Decarbonizing petroleum with direct air capture and enhanced oil recovery

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ABSTRACT

This study reports the cradle-to-wheel life cycle greenhouse gas (GHG) emissions resulting from enhanced oil recovery (EOR) using CO_2 sourced from direct air capture (DAC). A Monte Carlo simulation model representing variability in technology, location, and supply chain is used to model the possible range of carbon intensities (CI) of oil produced through DAC-EOR. Crude oil produced through DAC-EOR is expected to have a CI of 449 tCO_2/mbbl. With 95% confidence, the CI is between 345 tCO_2/mbbl to 553 tCO_2/mbbl. Producing net-zero GHG emission oil through DAC-EOR is thus highly improbable. An example case of DAC-EOR in the U.S. Permian Basin shows that only in the unlikely instance of the most storage efficient sites using 100% renewable energy does DAC-EOR result in "carbon-negative" oil production.

1. Introduction

There is growing consensus that, in addition to deep cuts in greenhouse gas emissions (GHG), carbon dioxide removal (CDR) is required to meet the climate temperature goal of the Paris Agreement (Shukla et al., 2022). CDR involves the removal of carbon dioxide (CO_2) from the atmosphere and its durable storage in oceans, products, or geological formations. Currently, most of CDR is accomplished through afforestation and reforestation (Smith et al., 2023). This sort of land management approach to storing carbon has been shown to be difficult to verify and vulnerable to rapid release (Minx et al., 2018). Afforestation and other forms of CDR technologies, such as soil carbon sequestration and ocean fertilization also have concerning side effects including negative impacts on biodiversity and ecosystem changes, or limited carbon sequestration capacity due to sink saturation (Fuss et al., 2018). These perceived limitations have led to increasing interest in "technological" CDR such as direct air capture with carbon storage (DACCS), bioenergy with carbon capture and storage (BECCS), and sequestration of carbon in soil as biochar.

Virtually all integrated assessment modelling (IAM) scenarios that limit warming to below 2 °C involve large amounts of these technological forms of CDR (Smith et al., 2023). Among them, DACCS has garnered significant interest and investment because it is thought to avoid many negative side effects such as impacts on food security, biodiversity, and soil quality while providing scalability, verifiable carbon removal, and permanence when coupled with geological carbon storage (Minx et al., 2018).

All carbon capture technologies, whether used to reduce emissions as in carbon capture and storage (CCS) or to remove CO_2 directly from the atmosphere as in DACCS, require reliable and permanent CO_2 storage. Geological storage is the most attractive alternative because it is a mature, demonstrated technology, whereas options such as ocean storage are still at the research stage (Holloway et al., 2006). The hopes and expectations that CCS and DACCS will play the major roles laid out for them in climate stabilization scenarios rely on the assumption that there will be a very large amount of geological storage available to meet all carbon capture storage needs (Lane et al., 2021).

There are several types of geologic storage defined by the different formations in which carbon is stored: depleted oil and gas fields, existing hydrocarbon reservoirs through enhanced oil recovery (EOR), deep saline aquifers; un-mineable coal seams; and basaltic formations (Albertz et al., 2023; Ali et al., 2022). Among these, CO_2 enhanced oil recovery (CO_2-EOR) is attractive because it is a mature technology that, in contrast to other forms of storage, produces valuable hydrocarbon

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coproducts that increase the profitability of depleting oil fields (Albertz et al., 2023). For this reason, coupling the expensive process of CCS with CO_2-EOR is a popular concept and 22 of 27 CCS projects globally include CO_2-EOR (Stone and Psarras, 2022). Pairing DAC with EOR (DAC-EOR) offers the possibility to simultaneously remove CO_2 from the atmosphere and enhance oil recovery.

In CO_2-EOR, some portion of the injected CO_2 remains below ground. If the injected CO_2 is captured directly from the air as in DAC-EOR, it is possible that the recovered oil could result in net-zero or even net-negative carbon emissions. However, the amount of CO_2 that is geologically stored per unit of oil produced critically depends on factors such as the ratio of crude oil recovered to CO_2 stored in the reservoir (CRR), the amount of CO_2 that returns to the surface with the recovered oil or through abandoned wells or other geological conduits to the surface.

The goals of EOR, to produce more oil while minimizing cost and CO_2 injected, conflict with the goals of geologic carbon storage. EOR operators want to minimize how much CO_2 they buy or must capture, as well as how much they use, and how much remains sequestered below ground. Absent government policy, EOR operators view CO_2 that remains below ground entirely as a cost. Section 45Q of the US tax code which provides a tax credit for carbon oxides—CO_2 and CO—that is stored through enhanced oil recovery (Jones and Sherlock, 2021) increases the amount of CO_2 that an EOR operator can use to produce a barrel of oil and still breakeven, but unless the value of the credit exceeds the cost of CO_2 capture and storage, the EOR operator is still motivated to minimize how much CO_2 they use.

Accounting for the 45Q tax credit of \$130/tCO_2, at an oil price of \$60/bbl, Datta and Krishnamoorti (Datta and Krishnamoorti, 2023) estimate that the EOR recovery ratio (CRR) must be greater than approximately 1.6 bbl/tCO_2 for the revenue from the sale of additional oil to exceed the cumulative cost of producing it. The injection of CO_2, when the CRR is below this level, would lower the carbon intensity of the oil produced, but since it would result in a net cost to the operator, it would not be done for oil recovery, but rather as CO_2 storage, some of the costs of which were offset through oil production. In this analysis, we evaluate the possibility of achieving net-zero GHG emission oil through the integration of DAC and CO_2-EOR for the primary purpose of oil production.

Multiple studies have quantified the net CO_2 emissions associated with CO_2-EOR using natural CO_2 occurring in underground gas domes, which is the most common practice (Cooney et al., 2015). Life cycle GHG emissions of CO_2-EOR have been evaluated for specific projects, sets of case studies, as well as at the country level (Jaramillo et al., 2009; Suebsiri et al., 2006; Abuov et al., 2022). Azzolina et al. (Azzolina et al., 2015) contributed to this body of work by analyzing data from 31 existing CO_2-EOR projects to develop general nonlinear functions that enable prediction from a handful of parameters of expected ranges of the CO_2 retention, incremental oil recovery, and net CO_2 utilization of projects.

Other studies have compared the life cycle CO_2 emissions of oil and gasoline produced with CO_2-EOR when CO_2 is obtained from anthropogenic sources other than DAC. Hussain et al. (Hussain et al., 2013) examined the life cycle GHG emission impacts of EOR using CO_2 from a variety of coal- and biomass-fired fuel and energy plants. Cooney et al. (Cooney et al., 2015) present a cradle-to-grave analysis of CO_2-EOR with the functional unit of 1 MJ of combusted gasoline incorporating a detailed gate-to-gate model of CO_2-EOR using predictive reservoir modeling. According to the authors, the oil recovery ratio (CRR) is a crucial factor in determining life cycle EOR emissions. Azzolina et al. (Azzolina et al., 2016) builds on the work of Cooney et al. (Cooney et al., 2015) by incorporating improved ranges for CO_2 storage (developed in their previous work (Azzolina et al., 2015), and examining a CO_2-EOR system in which CO_2 is sourced from a coal-fired power plant. In this scenario, oil produced from CO_2-EOR is found to have an emission factor that is slightly lower than that of conventional oil (438 kg CO_2e/bbl compared to ~500 kg CO_2e/bbl) (Azzolina et al., 2016).

Sminchak et al. (Sminchak et al., 2020) report the successful production of net-negative emission oil based on operational records from a set of mostly new projects within a CO_2-EOR system in the Northern Michigan Basin, U.S. This system, however, has several unique characteristics that make it fundamentally different from typical CO_2-EOR floods in areas like the Texas Permian Basin. Crucially, the analysis was performed when most of the individual CO_2-EOR projects were less than 10-years old and two were still in the injection/CO_2-fillup stage. This timing amplifies the apparent CO_2 storage because, as a displacement process, all CO_2 operations start out carbon negative. At the beginning of operation large amounts of CO_2 are injected into the subsurface reservoir to displace oil toward the extraction wells. Years into the project, as oil production increases, the carbon footprint becomes increasingly positive (Núñez-López and Moskal, 2019).

Several studies have also examined the life cycle performance of DACCS, but only a few in conjunction with EOR, and none estimate the carbon intensity of oil produced using DAC-EOR. De Jonge et al. (de Jonge et al., 2019) evaluated the life cycle carbon efficiency of a strong hydroxide DAC system and found that carbon efficiency, defined as the amount of carbon stored per amount of carbon captured, might range from 10% to 93% depending most on the source of energy. Focusing on low-temperature DACCS systems, Terlouw et al. (Terlouw et al., 2021) also found that energy supply was the key factor driving GHG emissions and emphasized the need to also consider variability in DACCS configurations. Bashti et al. (Bashti et al., 2022) analyzed the use of DAC-EOR for carbon storage using the "system expansion" LCA technique which assigns to the produced oil the carbon intensity of oil produced through conventional means, and thus does not evaluate the carbon intensity of the crude produced using DAC-EOR.

The commercial DAC plants operated by Climeworks in Hinwil and Hellisheiði, Iceland, were found by Deutz and Bardow (Deutz and Bardow, 2021) to achieve carbon capture efficiencies of 85.4% and 93.1% respectively. The Hellisheiði plant uses geothermal energy to produce both electricity and heat, while the Hinwil plant sources electricity and waste heat generated from a collocated waste-to-energy plant. Qui et al. (Qiu et al., 2022) performed prospective LCA of DAC with geological storage using integrated assessment modeling. The environmental performance of DACCS technologies is found to be interdependent with the energy system and different paths to low-carbon energy sources lead to environmental trade-offs.

This analysis of the net carbon emissions of DAC-EOR is particularly timely because the concept of DAC-EOR is rapidly moving toward commercialization. 1PointFive, a subsidiary of Occidental Petroleum's Oxy Low Carbon Ventures business has announced its intention to use DAC-EOR to produce "net-zero oil" by injecting enough captured atmospheric CO_2 through EOR to offset the CO_2 emissions from the entire crude oil life cycle from extraction through combustion (Write, 2022). Some in the oil industry see huge potential growth in EOR. For instance, Advanced Resources International (Godec, 2020) estimates that 284 billion barrels of oil that could not be extracted with primary or secondary technologies are accessible with CO_2-EOR, and 80 billion barrels are economic at 2020 oil prices, but extraction would require 40 billion metric tons of CO_2. DAC is an essentially unlimited source of CO_2.

Not surprisingly, the DAC-EOR concept is controversial. DAC on its own is controversial because it can be seen as an excuse for limiting CO_2 emissions reductions today because DAC provides a way to remove carbon from the atmosphere in the future (Malm and Carton, 2021). DAC-EOR and CCS-EOR come with the added concern that they are excuses for continued oil and gas production, allowing CO_2 emissions to continue when climate goals require steep emission reductions (Scott and Salvin, 2023). The decision in 2022 by the US Department of Energy to allow the funding of DAC-EOR projects under its Regional Direct Air Capture Hubs program was decried as a new taxpayer subsidy of oil and gas production (Axelrod, 2022). In the U.S. State of California these concerns have led to the passage of legislation that bans EOR that uses

CO_2 from carbon capture, with the stated aim of facilitating “the transition to a carbon-neutral society and not to facilitate continued dependence upon fossil fuel production” (Limon et al., 2022).

While several studies have explored the feasibility of DAC-EOR systems, most have focused on economic aspects (Datta and Krishnamoorti, 2023; Fasihi et al., 2019; McQueen et al., 2020; Jiang et al., 2023). The question of whether DAC-EOR is likely to produce net-zero (or even carbon-negative) oil has not to our knowledge yet been addressed in the literature.

We have addressed this gap by conducting a detailed life cycle analysis of GHG emissions associated with crude production using DAC-EOR from the ground up. We have developed a probabilistic model, as discussed in Section 3.1, that accounts for variability in technologies, locations, and supply chains, and use this model to estimate the variance in the CI of crude oil production that results from the range of locations and operating parameters analyzed. We used the Permian Basin as an example case to analyze potential changes in technology and energy production, such as the use of 100% renewable energy for heat and electricity, which allowed us to explore the future potential for low carbon intensity crude produced through DAC-EOR.

2. Methods

The cradle-to-wheels DAC-EOR system modeled includes: 1) capture and compression of CO_2 from the atmosphere at the DAC unit, 2) transportation of the compressed CO_2 to the EOR site, 3) injection of CO_2 with brine into the oil reservoir for crude oil recovery, 4) transportation of the recovered crude to a refinery, 5) distillation of crude into products, and 6) product use in an internal combustion vehicle (Fig. 1).

GHG emissions from each life cycle stage are calculated independently, with the DAC and EOR stages connected by CO_2 mass flows, as indicated by dashed arrows in Fig. 1. Calculations begin by selecting the Net Utilization of Carbon (NUC), which is the inverse of the crude recovery ratio (mbbl/tCO_2) and defines the tons of CO_2 stored underground per thousand barrels of crude oil produced. NUC is then used to back-calculate the required CO_2 for injection and capture from the DAC plant, accounting for losses during transportation and EOR operations. Life cycle stages following EOR are connected through the volumetric flow of crude oil, shown by solid black arrows in Fig. 1. Total life cycle GHG emissions, reported per 1000 barrels and defined as carbon intensity (CI), are calculated using Eq. (1).

$$CI_{DAC\ EOR} = CI_{DAC} + CI_{CO_2\ pipeline} + CI_{EOR} + CI_{crude\ transport} + CI_{refinery} + CI_{downstream} \quad (1)$$

The CIs account for GHG emissions from the construction and maintenance of infrastructure, raw material procurement and its replenishment, energy use in operation and related process emissions. However, when modeling these aspects for a life cycle stage, significant variance in inputs to the model arises due to geographical and technological differences. For example, the CI of electricity will vary depending on the location of crude extraction. To account for these variabilities, we employ a Monte Carlo simulation model, where input variables are defined as continuous probability distributions (CPDs). The CPDs are chosen based on empirical data when possible. When available data or the literature do not provide a CPD, we rely on expert opinion or use maximum entropy distributions (MEDs) (Conrad, 2004). MEDs are derived by maximizing information entropy based on available data, producing the least biased CPD for an uncertain variable. Tribus (Tribus, 2013) derives MED for different cases that are used in the current study. When only a variable’s limits are known, its MED becomes a uniform distribution. When the limits as well as a mean value are available, the MED is a truncated exponential function. Similarly, when the limits, mean, and standard deviation are known, the MED is a truncated normal distribution. Details on the data and assumptions used in calculating the CI of each life cycle stage are discussed below. Results from the Monte Carlo simulations are used to quantify the sensitivity of the overall CI to variation in input parameters using Spearmen’s rank correlation coefficient.

2.1. Carbon intensity calculations

The following section discusses the modelling approach used in each life cycle stage including the sources of data, distributional form, and assumptions made.

2.1.1. Direct air capture (DAC)

The CI of DAC is modelled based on the two most advanced technological alternatives commercially available: high temperature aqueous DAC (A-DAC) and low temperature solid DAC (S-DAC), which have been commercially demonstrated by Carbon Engineering and Climeworks respectively (Climeworks Switches on World’s Largest Direct Air Capture Plant 2024; Climeworks Becomes World’s First Direct Air Capture Company Certified under the Puro Standard 2024; Engineering of World’s Largest Direct Air Capture Plant Begins 2019; Occidental 2022; Gelles, 2024).

The general mechanism for DAC begins with the sorption of CO_2 from ambient air to a sorbent, followed by separation, which produces CO_2 and regenerates the sorbent. The energy consumption in this process depends on the type of sorbent and regeneration technique used. The alkaline-aqueous sorbent and high temperature decomposition of carbonates to produce CO_2 utilized in A-DAC requires 2.78 MWh/tCO_2 of thermal energy (H_a) and 0.366 MWh/tCO_2 of electricity (E_a) (Keith et al., 2018). S-DAC’s solid-amine adsorbent requires 2.5 MWh/tCO_2 of thermal energy (H_s) and 0.5 MWh/tCO_2 of electricity (E_s) (Evans, 2017). These figures, although sourced directly from the technology providers,

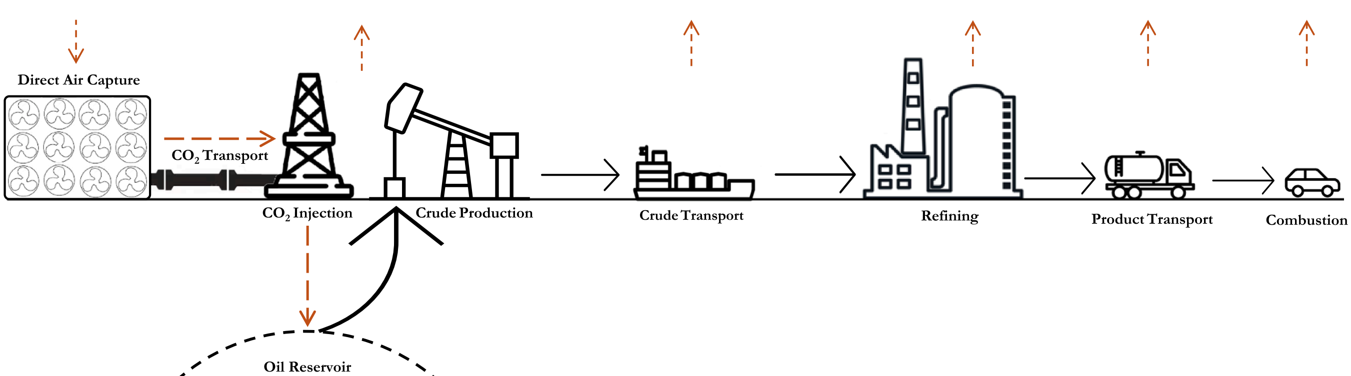

Fig. 1. System Boundary: Illustration of the process flow and system boundary used for the assessment of carbon-intensity of oil produced via EOR using CO2 captured directly from the atmosphere, where dashed orange arrows represent the flow of CO2 while solid black arrows denote the flow of crude oil and its derivative.

are consistent with independent studies analyzing the economic feasibility of similar technologies (Datta and Krishnamoorti, 2023; Fasihi et al., 2019; McQueen et al., 2020; Jiang et al., 2023). For each iteration of the Monte Carlo simulation, a technology is randomly selected, and its energy use is multiplied by the CI of the corresponding energy source to calculate the CI of DAC (CI_{DAC}), as given by Eqs. (2) and 3.

The source of heat for both technologies is assumed to be natural gas (NG) combustion. The CO_2 released from combustion is re-captured at an efficiency of 90% and is added to the total throughput of the plant (CO_2 injected in Eq. (2) and 3). The CI of NG combustion in the US (CI_{NG}) is taken from a review of electricity generated from NG (Jordaan et al., 2022). The reported CI per kWh-electricity produced is converted to kWh of NG combusted based on the efficiency of the combustion process (US U.S. Energy Information Administration: Oct 2023, 2023).

Our model estimates the CO_2 required for injection based on the crude recovery ratio which is the reciprocal of net carbon utilization. The DAC unit provides this injected CO_2 which is captured from the atmosphere and from CO_2 resulting from powering the DAC unit. We calculate the amount of CO_2 captured from the atmosphere through a mass balance on these flows (Eq. (3)).

The CI of electricity use on state level in the US is available in the eGRID database (United States Environmental Protection Agency (EPA) 2022). The state-level crude oil production using CO_2-EOR is published by ARI (Wallace, 2021). The weighted average of CI of electricity (CI_{elec}) is calculated by multiplying it with the oil production of the state. The standard deviation, the minimum and the maximum value of CI_{elec} are estimated from the egrid database. The calculation of weighted mean assumes that DAC plant and the EOR site are within the same state boundary. Incorporating the variance in CI of natural gas and electricity, which indirectly accounts for the impact of geographical conditions has been shown to significantly influence the CI of DAC (An et al., 2022; Sendi et al., 2022). The $CI_{infra\ DAC}$ is the combined CI of infrastructure and sorbent replenishment for both technology types (Madhu et al., 2021).

$$CI_{DAC} = \left(\left(0.1 \times (H_a\ OR\ H_s \times CI_{NG}) + H_a\ OR\ H_s \times CI_{elec} + CI_{infra\ DAC}\right) \times CO_{2\ injected}\right) - CO_{2\ Captured} \tag{2}$$

$$CO_{2\ Captured} = CO_{2\ injected}(1 - 0.9 \times (H_a\ OR\ H_s \times CI_{NG}) + H_a\ OR\ H_s \times CI_{elec}) \tag{3}$$

2.1.2. CO_2 transport-Pipelines

The pipeline for the transportation of CO_2 from the DAC plant to the EOR site is designed using the Integrated Environmental Control Model (IECM), assuming a throughput of 1 Mt-CO_2/yr. IECM utilizes fluid and flow properties of CO_2 to estimate the required pressure difference and the nominal diameter (Berkenpas et al., 1999). The pipe thickness is calculated using the results from the model using Eq. (4) given by the US code of Federal Regulations (Pipeline and Hazardous Materials Safery Adminmistration).

$$pipeline\ thickness\ (t; inch) = \frac{p_{mop}\ D_0}{2\ SEF} \tag{4}$$

In Eq. (4), p_{mop} is the maximum operating pressure in the pipeline (15.3 MPa), D_0 is the outer diameter of the pipe, S is the minimum yield stress for commercial steel pipe (483 MPa), E is the longitudinal joint factor (1), and F is the design factor (0.72). The value of S and F are taken from the American Petroleum Institute specification for API 5L- X-70-line pipe meant for CO_2 transport (Mccoy and Rubin, 2008).

The calculated pipe thickness (t) and the outer diameter (D_0) are used to calculate the inner diameter of the pipe (D_i), which is used to calculate the total amount of steel that went into the construction of pipeline, using Eq. (5). The density of steel (ρ) is assumed to be 7900 kg/m^3 (Sutherland, 2004). The pipe length (l) is the distance between the DAC plant and the injection well and defined as uniform distribution with the range 0–150 km, since the advantage with DAC over other sources of CO_2 is that it could be set up near the EOR site. Subsequently, the overall GHG emissions from pipeline construction are quantified by multiplying the mass of steel obtained from Eq. (5) with the CI of steel making which is approximately 2.12 kgCO_2eq/kg-steel (Mccoy and Rubin, 2008). Energy usage in creating the pressure differential is considered negligible, as the initial CO_2 compression driving the flow is accounted for within the DAC plant's energy consumption. However, recompression stations after every 60–160 km are required to maintain the flow which utilizes around 1.43 kWh/t-CO_2 ($E_{re\text{-}compression}$) for compression from 10 MPa to 15.4 MPa (Mccoy and Rubin, 2008) (Eq.7).

$$Mass\ of\ Steel\ (kg) = \rho\pi \times \frac{(2D_0 - t)(t)}{4} \tag{5}$$

The leakage is derived from a national sampling study of natural gas distribution across the US which reports the mean and the range of fugitive emissions from pipeline and meters, as percentages of total mass transported (Lamb et al., 2015). The overall CI of pipeline transport of CO_2 process is given by Eq. (7).

$$CI_{recompression} = \frac{E_{re-compression}}{100\ km} \times distance \times CI_{elec} \tag{6}$$

$$CI_{pipeline\ CO_2} = \left((\rho_{steel} * Mass\ of\ Steel\ ) + CO_{2\ injected} \times leakage\right) + CI_{recompression} \tag{7}$$

2.1.3. CO_2-Enhanced oil recovery

The CI of EOR is calculated following NETL (Skone et al., 2013) (for a summary of this method see Cooney et al. (Cooney et al., 2015)). EOR is modeled as a typical water-alternating-gas (WAG) CO_2-EOR operation in a conventional reservoir. The recovered gas, which is a mixture of CO_2 and other hydrocarbon gases (HC-gas) is separated, and the recycled CO_2 is reinjected into the reservoir. The model utilizes the reservoir's NUC and internal mass flow rates to characterize reservoir behavior. NUC is defined as tons of CO_2 permanently sequestered for thousand barrels of crude oil produced and is determined by a combination of the reservoir characteristics and the operating conditions. Multiple reservoir characteristics, including reservoir depth, thickness, pore volume, well pattern, and injection pressure are embedded in the NUC (Skone et al., 2013). In our analysis, *NUC* values are derived using the general predictive functions developed by Azzolina et al. (Azzolina et al., 2015) at the median cumulative injection volume of 250% (i.e., the cumulative volume injected is 2.5-times the hydrocarbon pore volume).

The flowrates of injected and recycled CO_2 are calculated from the *NUC* using Eqs. (8) and 10 in which the CO_2 retained ($\eta_{retention}$ is the portion of the gross injected CO_2 (recycled CO_2 + fresh CO_2) that stays in the reservoir through its residual trapping in pore spaces, solubility trapping in reservoir fluids, and mineral trapping as stable carbonate compounds, and CO_2 stored ($\eta_{storage}$) is the portion of cumulative fresh injected CO_2 that is stored in the reservoir (Azzolina et al., 2015; Perera et al., 2016). Other internal mass flow rates like brine injection, production, and HC gas production are described using empirically derived power-law Eqs. (11-13)[16], (Azzolina et al., 2016). The calculated mass flow rates are multiplied by their specific energy (SE) utilization to determine the energy used in CO_2 compression, brine injection and brine disposal. Since NETL (Skone et al., 2013) reports only singular values of SE, the CPD of SE is defined as a uniform distribution, with a range of ±10% around the reported value. Including SE explicitly allows it to be included in the sensitivity analysis, while variation across reservoirs is accounted for in the calculated mass flow rates.

$$CO_{2_{injected}}(t\,/\,mbbl) = \frac{NUC}{\eta_{storage}} \tag{8}$$

$$CO_{2,\ gross}\ (t\,/\,mbbl) = \frac{CO_{2,\ injected}}{\eta_{retention}} \tag{9}$$

$$CO_{2,\ recycled}\ (t\,/\,mbbl) = CO_{2,\ gross} - CO_{2,\ injected} \tag{10}$$

$$Brine_{\ injected}\ (kg_{brine}\,/\,kg_{crude}) = 52.5\ \times NUC^{-1} \tag{11}$$

$$Brine_{\ produced}\ (kg_{brine}\,/\,kg_{crude}) = 56.7\ \times NUC^{-1} \tag{12}$$

$$HC\ gas_{\ produced}\ \left(kg_{HC\ gas}\Big/\,kg_{crude}\right) = 0.62\ \times NUC^{-1} \tag{13}$$

The energy required in artificial lifting of crude is linearly related with the depth of the reservoir (Dilmore, 2010). The data on crude production from various reservoir depths are published by ARI (Wallace, 2021), which is utilized to calculate the weighted-mean depth (weighed by crude production rate) and other MED parameters. Gas separation is assumed to employ the Ryan Holmes method that uses only electricity. Therefore, its energy usage is converted to equivalent emissions using CI_{elec}. The throughput of the gas separation unit is approximated as the sum of CO_2 produced and HC gas.

In addition to this, emissions associated with construction and land use $(CI_{infrastructure\ EOR})$ are assumed for land utilization of 0.25 acres per well and 20 acres for the gas processing facility (Cooney et al., 2015). The process emissions from EOR include the CO_2 produced at the end of life of the EOR operation which is not recycled but released into the atmosphere (approximately 5%) and other emissions, like flaring and venting of methane $(CI_{venting\ and\ flaring})$ that is produced during oil production and storage is assumed to be 3.4 $kgCO_2$/bbl-crude (Cooney et al., 2015). The emissions from formation leakage are assumed to be zero (Azzolina et al., 2016). The distribution of process emissions and emissions from infrastructure are defined as uniform with a range of ±10% around the calculated value. The overall CI of EOR is given by Eq. (14).

$$\begin{aligned} Electricity_{EOR} = \big(&CO_{2,\ recycled} \times SE_{compression} + Brine_{\ injected} \times\ SE_{brine\ injection} \\ &+ Brine_{\ produced}\ \times SE_{produced} +\ \big(HC\ gas_{\ produced} \\ &+\ CO_{2\ recycled}\big)\ \times\ SE_{Gas\ seperation}\big) +\ SE_{Artificial\ lift} \end{aligned} \tag{14}$$

$$CI_{EOR} = Electricity_{EOR}\ \times CI_{elec} +\ CI_{infrastructure\ EOR} + CI_{venting\ and\ flaring} \tag{15}$$

2.1.4. Crude transport, refining and combustion

The extracted crude is transported via a network of pipelines, roadways, or railways to a port for export or a domestic refinery. Based on the current crude import to export ratio, it is assumed that 50% of the total oil produced is exported while the other half is refinery domestically (Share $_{domestic}$) (U.S. Energy Information Administration 2023). Pipeline and railroads share 92.5% ($Share_{pipeline}$) and 4.9% of the domestic transportation load respectively (U.S. Department of Transportation Bureau of Transportation Statistics 2021). CI of pipeline transportation ($CI_{pipeline}$) of crude has been published by Choquette-Levy et al. (Choquette-Levy et al., 2018). The distance of crude transport is assumed to have a range of 50–1000 kms. CI for marine transport ($CI_{marine\ transport}$) of crude is taken from the GLEC Framework 2019 report (Greene and Lewis, 2019). There, different CIs are available based on weight class—of the ship—and fuel type. The average value is represented by an oil tanker of 179,000 deadweight tons using heavy fuel oil (Greene et al., 2020). The average distance between the US and each destination country (Sea-distances) is weighed based on the amount of crude exported to that country (US U.S. Energy Information Administration: Oct 2023, 2023) to calculate the mean export distance. The CI of crude oil transport is given by Eq. (16).

The CI of refinery ($CI_{refinery}$) estimates for each crude type (by source) is given by Jing et al. (Jing et al., 2020) utilizing the Petroleum Refinery Life Cycle Inventory Model. Additionally, to represent further opportunities to reduce emissions, the prospective use of CCS at the refinery is included in the model with a maximum efficiency of 90%.

The CI for combustion of products ($CI_{combustion}$) is determined using the 2022 U.S. EPA Inventory of Greenhouse Gas Emissions and Sinks (Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2020 2022), with an average carbon coefficient of 1.93×10^{-2} kg carbon/MJ. Given that 0–7% of the carbon in each oil barrel remains in non-combustible products like asphalt and considering an average heat content of 6120 MJ/bbl, the emission factor is set at 430 tCO_2/mbbl, with a range between 400 and 430 tCO_2/mbbl (Jaramillo et al., 2009; Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2020 2022). The overall CI of downstream process is given by Eq. (17).

$$\begin{aligned} CI_{crude\ transport\ and\ combustion}\ = \big\{&Share_{domestic}\ \big(\ Share_{pipeline} \times\ CI_{pipeline\ transport} \\ &+ (1 - Share_{pipeline}) \times\ CI_{non-pipeline}\big) + (1 \\ &- Share_{domestic}) \times\ CI_{marine}\big\} \end{aligned} \tag{16}$$

$$CI_{downstream}\ = CI_{crude\ and\ transport} + CI_{refinery} + CI_{combustion} \tag{17}$$

2.2. Example case

An example case of the Permian Basin is developed to explore potential improvements in the DAC-EOR process and illustrate impacts at each life cycle stage. This region has had the highest share of oil production from EOR across all basins in the US over the last two decades and is one of the most studied regions in EOR literature. (Cooney et al., 2015; Wallace, 2021; Dilmore, 2010; Kuuskraa et al., 2013). A baseline scenario is developed in which the contributions to the overall CI of each life cycle stage are quantified using equations (1–16), with input values that represent current practice in the US Permian Basin. Specifically, the input values include the use of Carbon Engineering's DAC technology, CI_{elec} of 0.386 tCO_2/MWh, and a higher NUC of 450 tCO_2/mbbl (Occidental 2022; United States Environmental Protection Agency (EPA) 2022; Karacan et al., 2023). These parameters respectively indicate the DAC technology projected for deployment in the Permian Basin, the Texas grid's carbon intensity, and the estimated NUC for the region (Occidental 2022; United States Environmental Protection Agency (EPA) 2022; Karacan et al., 2023). Additional scenarios are created to explore the impacts of best practice and technological advancements in the inputs and technologies to which the overall CI is found to be most sensitive. Scenarios are built around these variables with a high rank correlation coefficient and the resulting overall CI is compared to the baseline scenario.

3. Results and discussion

3.1. Monte carlo simulation

The life cycle emissions for oil extracted through DAC-EOR, resulted in a mean value of 449 tCO_2/mbbl, with a range of 345–553 tCO_2/mbbl at a confidence level of 95%, as shown in solid red in Fig. 2(a). The resulting distribution has a skewness of 0.17 and a kurtosis of 0.55, which visually translates to a skew to the right, a preponderance of lower-than-average CIs, and higher likelihood of outliers compared to a normal distribution. Thus, crude produced though this route did not achieve net zero life cycle emissions in any of Monte Carlo iterations and had a minimum value of 249 tCO_2/mbbl. Nevertheless, DAC-EOR significantly reduces GHG emissions when compared to conventional crude—18.36 % vs. a wells-to-wheels CI of 550 tCO_2/mbbl for conventional crude (Jaramillo et al., 2009; Masnadi et al., 2018).

The results of the sensitivity analysis are presented in Fig. 2(b), which highlights the ten most influential variables in determining the overall CI of DAC-EOR. The two most sensitive variables are the carbon intensity of process heat in DAC and the electricity used throughout the process, with correlation coefficients of 0.62 and 0.48, respectively. This

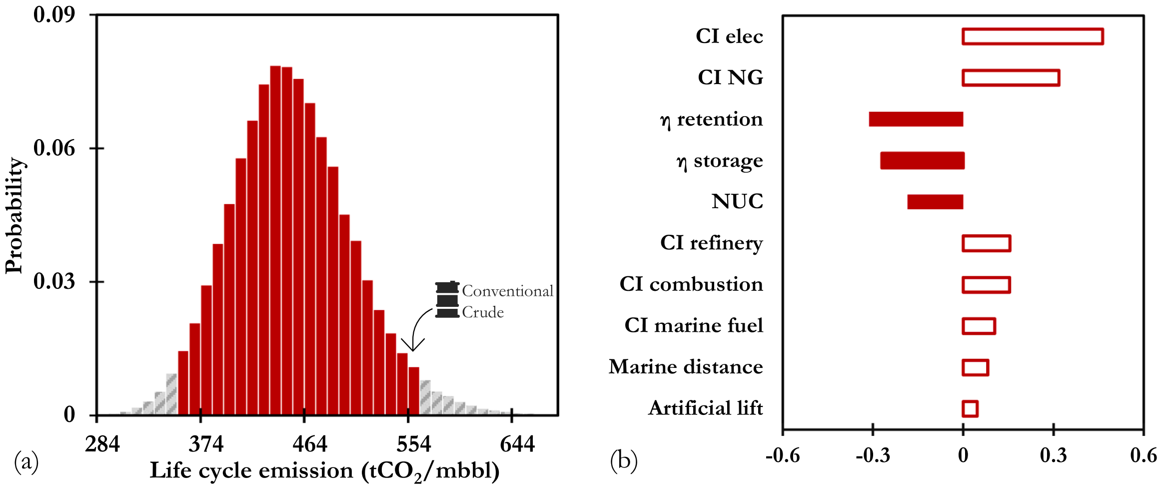

Fig. 2. (a) Life cycle emissions in CO2 eq per thousand barrels of crude produced from DAC-EOR. The range with a confidence level of 95% is shown in solid/cardinal red and compared to conventional crude (marked by a barrel symbol) (b) Sensitivity analysis of ten most important input variables in determining life cycle emissions of the system; sensitivity quantified with rank co-relation coefficient.

indicates that energy sources are the most crucial factors affecting CI. Reducing CI_{NG} by sourcing low-carbon fuels and using cleaner electricity, such as dedicated renewable power from wind or solar PV, would substantially lower the overall CI.

Following CI_{NG} and CI_{elec}, the next most influential parameters are η storage, η retention, and NUC, which define reservoir characteristics and have significant inverse influence on overall CI, with coefficients of −0.31, −0.28, and −0.22, respectively. The parameter $\eta_{retention}$ represents the percentage of CO_2 that remains underground per injection cycle. A lower $\eta_{retention}$ indicates that more CO_2 is produced at the extraction well, increasing the energy required for CO_2 separation and compression for re-injection. The $\eta_{storage}$ parameter represents the cumulative CO_2 stored underground, so larger values mean less CO_2 is released back into the atmosphere with oil production. NUC, equivalent to the amount of CO_2 stored per barrel of oil produced, also inversely impacts CI. More CO_2 injected per barrel of oil results in a lower CI for the oil. This negative correlation is consistent with the definitions of $\eta_{retention}$, $\eta_{storage}$, and NUC, aiding in site selection for a lower-carbon EOR process.

The sensitivities of overall CI to $CI_{Combustion}$, and $CI_{Refinery}$ are similar and slightly less than that of NUC, with correlation coefficients of 0.159, and 0.156, respectively. Reported per barrel of crude, $CI_{Combustion}$, is perhaps nonintuitively unaffected by improved combustion efficiency because of the fixed carbon content in a barrel of oil. The carbon intensity of refinery operations, $CI_{Refinery}$, is driven primarily by energy use in refining. Although $CI_{Refinery}$ could be lowered through CCS at the refinery, it has so far been found to be not economically viable. (Yao et al., 2018)

The transportation parameters $CI_{Marine\ fuel}$ and *marine distance*, have correlation coefficients of 0.086 and 0.079, which reflects the relatively low impact of long-distance ocean shipping of crude on the overall CI. The impact of shipping could be mitigated by using low-carbon or sustainable marine fuels. Lastly, *artificial lift* has a correlation coefficient of 0.043, and represents the electricity required to lift crude to the surface at the extraction well.

In summary, sensitivity analysis indicates that the sources of process energy and the crude oil reservoir characteristics have the largest influence on the overall CI of the produced oil.

3.2. Example case

Use of DAC-EOR to produce crude oil in the Permian Basin example case has a baseline overall CI of 426 tCO_2/mbbl – this is the business-as-usual scenario shown in Fig. 3(a) - which is approximately 22% lower

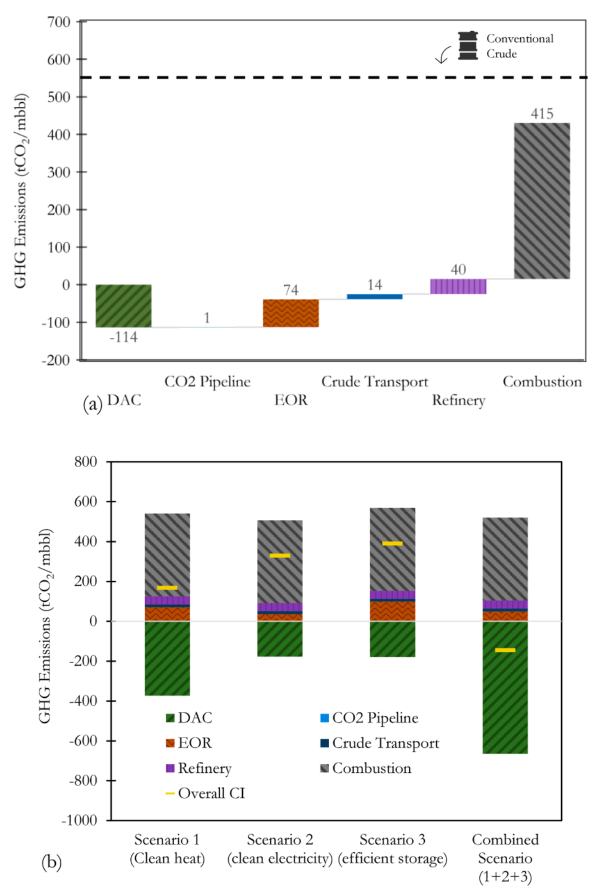

Fig. 3. (a) Baseline Scenario in the Permian Basin: This figure shows the GHG emissions contributed by each stage of the DAC-EOR process for the baseline scenario to produce a thousand barrels of crude in the Permian Basin, measured in tCO2(eq). (b) Future Scenarios: (b) compares the carbon intensity of three future scenarios: Scenario 1 focuses on adopting clean thermal energy; Scenario 2 examines the impact of using renewable energy for power generation; and Scenario 3 looks at the benefits of improved CO2 storage efficiency. The Combined Scenario reflects the impact of implementing in combination Scenarios 1–3.

than conventional crude, and 6% lower than the average CI reported in Section 3.1. The baseline value in the Permian Basin example case is lower than the average value of DAC-EOR in the sensitivity analysis because the electricity in this region has a somewhat lower CI and a higher NUC. In this baseline scenario, combustion contributed the largest fraction of emissions, 415 tCO_2/mbbl (77%). The next most important contributors to the overall CI were the EOR technology and the refinery process, with emissions of approximately 74 tCO_2/mbbl and 40 tCO_2/mbbl, respectively (13% and 7.5%). Crude oil transport via marine and land modes resulted in emissions of 14 tCO_2/mbbl (3%), while pipeline transport of CO_2 had a minimal impact, contributing only 1 tCO_2/mbbl (0.2%). These emissions were partially offset by the direct air capture (DAC) unit, which captured 21% of the gross emissions.

The example case includes three scenarios devised to explore the impacts of best practice and technological advancements in production of the inputs to which the overall CI is found to be most sensitive. Parameters with the largest impact on overall CI as revealed by sensitivity analysis are CI_{NG}, CI_{elec}, and NUC.

Scenario 1 represents the utilization of a low carbon heat source such as the use of electric kilns powered by renewable electricity. Assuming a net zero carbon source of heat, this scenario results in a reduction of 259 tCO_2/mbbl, 60% lower than the baseline. The other large use of energy is the consumed in various life cycle stages of DAC-EOR. In scenario 2, CI_{elec} is taken to be 11 g/kWh, representing use of 100% renewable wind electricity (Dolan and Heath, 2012). This leads to a CI reduction of 23% relative to the baseline. Scenarios 1 and 2, show potential for substantial reductions in the overall CI of DAC-EOR but are currently constrained by the availability of large amounts of low-carbon renewable energy. The relevance of these best-case, future scenarios using 100% renewable energy is not limited to the Permian Basin. As demonstrated by Terlouw et al. (Terlouw et al., 2021), the CI of 100% renewable energy varies little with geographic location.

Scenario 3 represents a DAC-EOR site in the Permian Basin at which the amount of CO_2 stored per crude oil produced (NUC) is the extreme value of the parameter distribution, i.e., 640 tCO_2/mbbl. This upper limit of CO_2 storage case results in a 38 tCO_2/mbbl reduction in overall CI which is 10% lower than the baseline scenario. Although a high NUC is impactful, for typical EOR operations a NUC of 640 tCO_2/mbbl is feasible at less than 3% of sites.

In this Permian Basin example case, scenarios 1 through 3 in combination - i.e., EOR with NUC of 640 tCO_2/mbbl, use of exclusively renewable energy electricity, and a carbon neutral source of DAC process heat — results in crude oil with net negative lifecycle GHG emissions (Fig. 3b). This case is particularly unlikely due to the extreme value of NUC required. Because NUC depends in part on physical reservoir characteristics, it cannot in an EOR context be managed to produce the extreme value in Scenario 1. For example, in a zero-carbon electricity and heat scenario and variable NUC, achieving net zero overall CI requires NUC of at least 500 tCO_2/mbbl, a NUC value achievable at approximately 25% of the EOR sites within the continental US.

3.3. Strengths and limitations

The derived distribution of DAC-EOR-produced crude oil reflects the expected variation in key system parameters across the supply chain and life cycle, including variation in technology, geography, and petrological factors weighted by regional crude production. It can be interpreted as the distribution of CI of the crude oil that would result if DAC-EOR were built-out at large-scale in North America but may not be universally generalizable. In addition, the sensitivity analysis provided reveals the key factors influencing CI which can guide identification of targets for technological improvement. This is essential information for those commercializing DAC-EOR and those developing policies to encourage the development and adoption of carbon capture technologies.

The example cases examined instantiate possible "best case" DAC-EOR scenarios, but these are limited in number and scope. There are many clean technologies that are actively being developed that might reduce the CI of future DAC-EOR. Our analysis also considered only conventional oil reservoirs and the use of the water alternating gas (WAG) injection method of EOR. While the use of WAG in conventional oil reservoirs currently dominates EOR projects, other EOR methods and EOR in non-conventional reservoirs may become more prevalent in the future. Our modeling approach results in a most likely value and distribution across geographies and technologies and so does not reflect the specifics of individual EOR projects, reservoirs, or refineries. There are particular possible DAC-EOR projects, represented by the low-CI tail of the distribution, that would produce very low CI crude oil. Although such projects would be attractive from a carbon removal perspective, as our results show, these sorts of opportunities are likely to be very uncommon.

4. Conclusion

Over a 30-year EOR production cycle, crude oil exhibited an average CI of 449 tCO_2/mbbl, with a 95% confidence interval ranging from 345 to 553 tCO_2/mbbl. This represents an 18% reduction in CI compared to conventional crude and indicating the unlikelihood of achieving net-zero. The emissions from the DAC-EOR system were predominantly due to combustion (77%), followed by EOR processes (13%), and refinery operations (7.5%). Use of DAC can offset 21% of these emissions. Key factors influencing the overall CI of DAC-EOR produced crude oil included the carbon intensity of heat, the carbon intensity of electricity, and the net utilization of CO_2, each playing a crucial role in determining the environmental impact of the EOR process. Evaluating future scenarios, such as the availability of 100% renewable electricity and heat, indicated that only one quarter of the wells in the continental US could potentially produce carbon-neutral oil.

CRediT authorship contribution statement

Jayant Singh: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Udayan Singh:** Visualization, Conceptualization. **Gonzalo Rodriguez Garcia:** Writing – review & editing, Writing – original draft. **Vikram Vishal:** Writing – review & editing. **Robert Anex:** Writing – review & editing, Writing – original draft, Supervision, Resources, Project administration, Methodology, Funding acquisition, Formal analysis.

Declaration of competing 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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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.ijggc.2024.104281.

Data availability

Data will be made available on reasonable request.

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