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Techno-Economic Assessment and Life Cycle Assessment of CO_2-EOR

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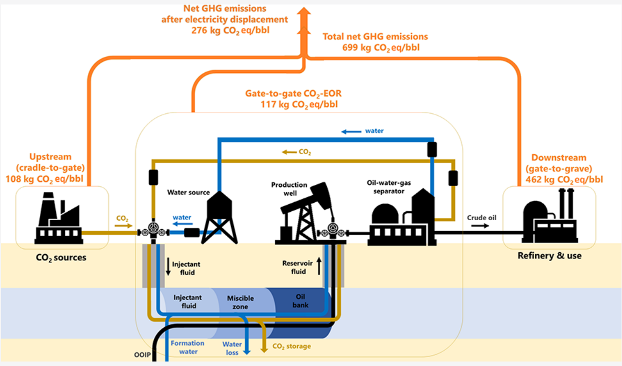
ABSTRACT: CO_2-enhanced oil recovery (EOR) can have less GHG emissions compared to conventional oil production methods. The economy of CO_2-EOR can significantly benefit from the recent rise of carbon prices in carbon markets due to its greenhouse gas (GHG) emission savings. This study conducted a life cycle assessment (LCA) of CO_2-EOR in major hydrocarbon provinces of the world. Estimated net GHG emissions of CO_2-EOR were compared with GHG emissions of average produced oil in the given country. When sourcing CO_2 from coal-fired power plants, Kazakhstan and China have net GHG emissions of CO_2-EOR of 276 and 380 kg CO_2 eq/bbl, respectively, which are lower than the GHG emission factor of average oil produced in each of them. Significantly lower GHG emissions of CO_2-EOR are observed in other hydrocarbon provinces (Iraq, Saudi Arabia, Kuwait, etc.), where CO_2 could be delivered from Natural Gas Combined Cycle (NGCC) power plants. However, the cost of CO_2 capture is higher at NGCC power plants than at coal-fired power plants. Further, we developed a techno-economic assessment (TEA) model of the CO_2-EOR and integrated it with LCA to thoroughly consider carbon credits in its economy. The model was built based upon previous investigations and used statistics from a large industrial data set of CO_2-EOR to produce accurate estimates of the CO_2-EOR economy. The technical model iteratively estimated the balance of three fluids (crude oil, CO_2, and water) in the CO_2-EOR system with a 25 year operational lifespan and obtained actual data for the LCA and TEA models. The model was simulated for the Kazakhstan case with its oil market conditions for a demonstration purpose. TEA results showed that, with the available low-cost CO_2 capture source or high CO_2 cost in carbon trading, CO_2-EOR can compete with current upstream projects in Kazakhstan by simultaneously increasing oil production and reducing GHG emissions.



KEYWORDS: *enhanced oil recovery, carbon market, GHG emissions, decarbonization, emission trading system, oil production cost, CCUS, Kazakhstan*

■ INTRODUCTION

Meeting the ever-pressing energy demands and greenhouse gas (GHG) reduction presents a seemingly intractable societal challenge. CO_2-enhanced oil recovery (CO_2-EOR) is a well-known technology that could satisfy the energy demands and GHG reduction goals by increasing oil production in oil reservoirs and permanently sequestering CO_2 in deep geologic formations.[1] CO_2-EOR is a tertiary oil recovery technology, as it has been typically used after primary and secondary means of oil production, recovering around 20−50% of the original oil in place (OOIP). CO_2-EOR can further recover the residual oil, representing another 5−20% of OOIP[2] via the following procedure: CO_2 is injected into the oil reservoir and mixed with reservoir fluids, which forms a single phase and reduces the viscosity of oil flowing toward production wells, thereby increasing the production rates of the reservoirs. Injecting CO_2 under geological formations can offset the total GHG emissions of CO_2-EOR, and net GHG emissions of CO_2-EOR are lower than those of conventional oil production methods.[3]

Despite its relatively eco-friendly nature, the geography of CO_2-EOR sites and related sustainability studies are mainly focused on North America,[2−7] where CO_2 is primarily sourced from natural CO_2 reservoirs,[8] which obviously do not contribute to GHG emission reduction goals. In the absence of relatively inexpensive CO_2 supplies from natural reservoirs, the cost of capturing anthropogenic CO_2 would be a significant hurdle that limits the use of CO_2-EOR. However, considering the continuous increase of CO_2 price at carbon markets in recent years,[9] soon the economy of CO_2-EOR might be able to

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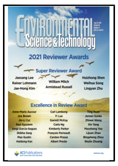

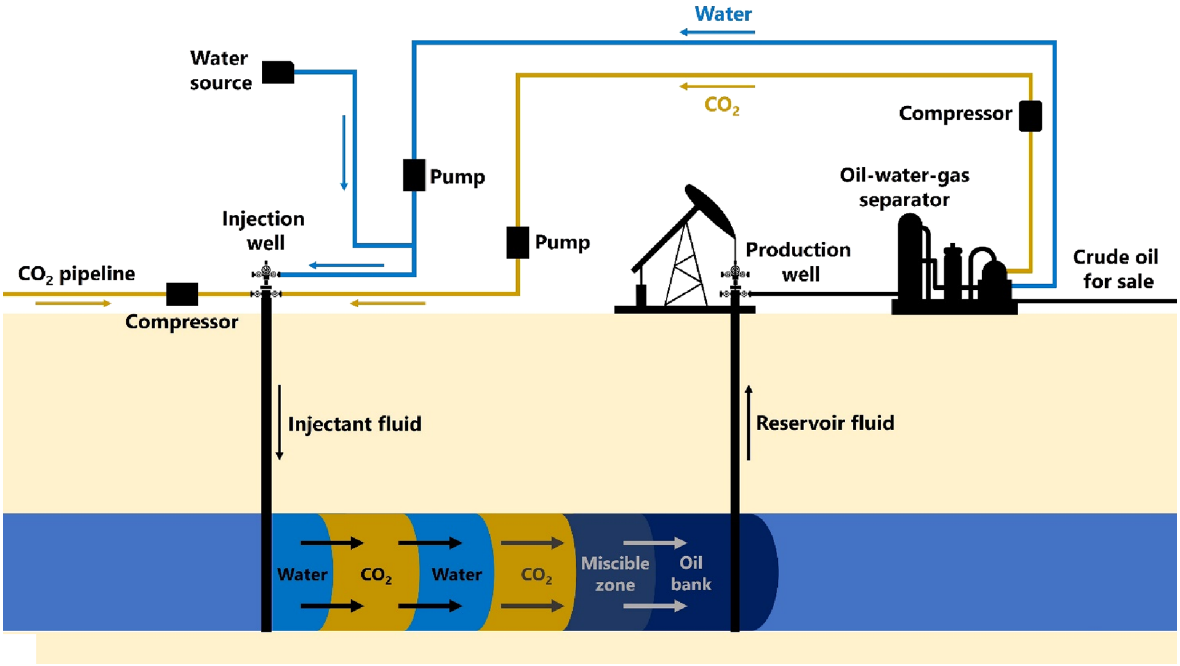

Figure 1. CO$_2$-EOR flow diagram with WAG technology.

compete with that of traditional oil production methods in many parts of the world. Measuring the sustainability of CO$_2$-EOR at a global scale faces scientific uncertainty due to specifics of processes that could be involved in the chain of anthropogenic CO$_2$-based EOR. Considering the potential role of CO$_2$-EOR for future large-scale carbon capture, utilization, and storage (CCUS) deployment and recent trends in the carbon markets, there is a necessity to study the sustainability of CO$_2$-EOR and its economy at a global scale using robust life cycle assessment (LCA) and techno-economic assessment (TEA) methods.

Several LCA and TEA models of the CO$_2$-EOR have been developed in the past and provided helpful information about the CO$_2$-EOR economy to date.[10−15] However, two main issues still have not been clearly addressed, causing an incomplete understanding of the CO$_2$-EOR. First, both LCA and TEA of CO$_2$-EOR are sensitive to the balance of CO$_2$ fluid in the CO$_2$-EOR system.[3,16] Net CO$_2$ utilization (mscf CO$_2$/bbl oil) or crude oil recovery ratio (bbl oil/t CO$_2$) is the parameter that has been used to estimate the balance of CO$_2$ in CO$_2$-EOR. It has been assumed to be constant in rule-of-thumb estimates of CO$_2$-EOR or evaluated in numerical reservoir simulations of fractional flow models.[11,13,14] The rule-of-thumb method is essentially inaccurate by its nature, as the net CO$_2$ utilization is a dynamic parameter that could be changed throughout the lifetime of CO$_2$-EOR.[17] The fractional flow model has been reported to underestimate CO$_2$ storage in CO$_2$-EOR[14] and thus can undermine carbon credits associated with the CO$_2$ storage in CO$_2$-EOR. Second, previous models cannot fully capture the technical, environmental, and economic performances of CO$_2$-EOR simultaneously. Carbon credits of the captured and stored CO$_2$ should be appropriately apportioned between CO$_2$ suppliers and CO$_2$-EOR operators. In light of the rising price of CO$_2$ in carbon trading markets, it needs to be accurately tracked down for a more precise understanding of the CO$_2$-EOR economy.

Our work has three principal contributions:

1. We perform the first country-level LCA of GHG emissions in CO$_2$-EOR, which covers the major hydrocarbon provinces of the world.

GHG emission credits of CO$_2$-EOR can alleviate its economy, and it has been demonstrated in the example of Kazakhstan using the newly developed TEA model of CO$_2$-EOR, which is comparable to the early models developed by McCoy (further modified by Wei et al.).[13,14] Our contributions also include two crucial differences in the CO$_2$-EOR model that aim to resolve the previously mentioned two issues in LCA and TEA models of CO$_2$-EOR:

2. The input data of the CO$_2$-EOR model uses the data of fluid balance of oil, CO$_2$, and brine from the real-world reservoir performance data of 31 CO$_2$-EOR sites processed by Azzolina et al.[3,17] Therefore, the model developed in this research can provide a realistic estimate of the CO$_2$-EOR economy.
3. Our TEA model is integrated with a cradle-to-grave LCA of crude oil derived from CO$_2$-EOR. Net GHG emissions from LCA are used in the TEA to estimate the carbon credits of the CO$_2$-EOR operator.

The model is entirely developed in a Microsoft Excel environment to make it transparent and available for the use of practitioners in the field. The spreadsheet model can be expanded or refined as new information becomes available. The spreadsheet model can be downloaded from the webpage of National Laboratory Astana (NLA).

Despite Kazakhstan's current energy and environmental status, that is, one of the largest hydrocarbon provinces and huge CO$_2$ emitters globally,[18,19] this is the first CO$_2$-EOR study conducted in the context of Kazakhstan and post-Soviet Union countries. The research has been carried out as part of the "KazCCUS" project that previously demonstrated the encouraging potential of CO$_2$ storage sites in Kazakhstan and suggested its CO$_2$-EOR opportunities.[20,21] Our work also aims to draw the attention of the local industry and research

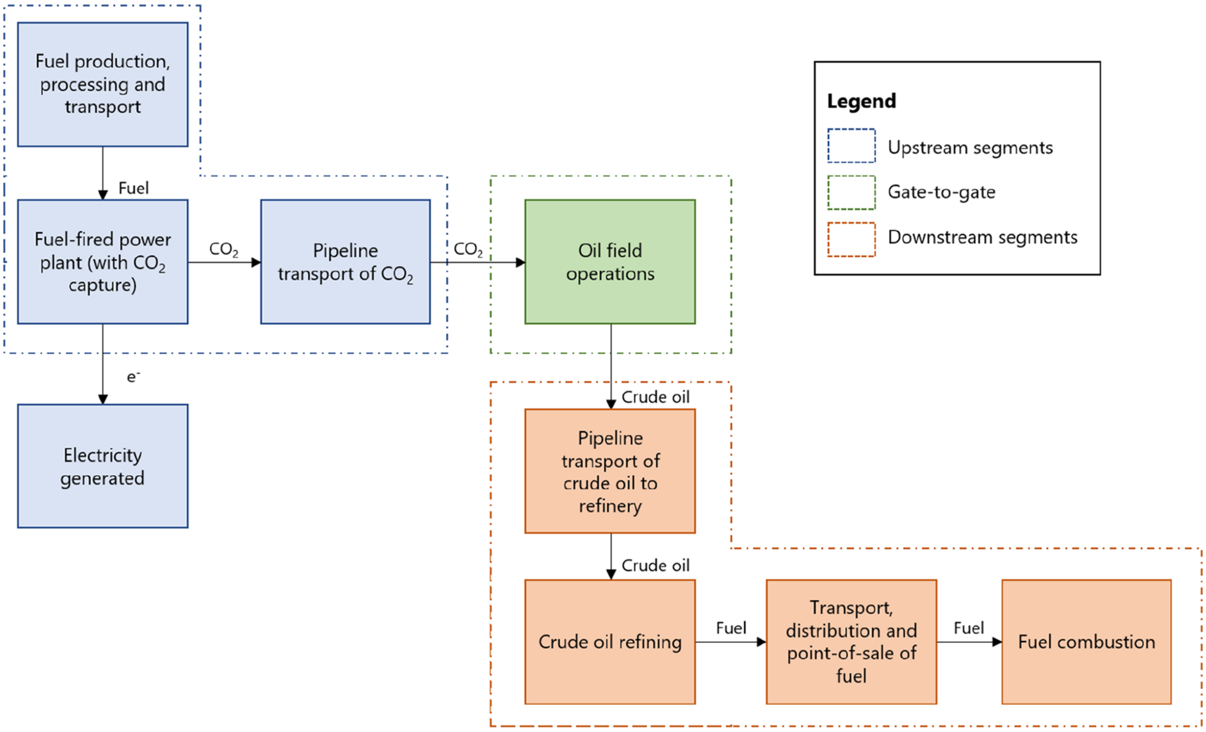

Figure 2. LCA boundaries of CO_2-EOR (oil is the main product and electricity is a coproduct) (adapted from refs 3 4, and 6).

community in the Caspian region to consider CO_2-EOR as a viable strategy to reduce GHG emissions.

■ METHODOLOGY

We assumed that the oil field had undergone primary and secondary production stages, where the latter implied waterflooding. CO_2-EOR was deployed as a tertiary recovery, where CO_2 was transported from the pulverized coal (PC) or natural gas combined cycle plant (NGCC) power plant with 85% CO_2 capture efficiency via pipelines. The power plant was fired with bituminous coal or natural domestic gas. The operator used water-alternating-gas (WAG) technology, where CO_2 injection was periodically altered with water injection to overcome the issues with gravity override, viscous fingering, and poor sweep efficiency that may happen when operating pure CO_2 flooding (Figure 1).[22]

The model developed in this study includes three main components: (1) technical model, (2) LCA, and (3) economic model. Each of the components was explained and discussed below. Extended descriptions and model assumptions are available in the Supporting Information.

Technical Model. The technical model estimated the fluid balance of oil, CO_2, and water in CO_2-EOR based on the regression relationships developed by US researchers.[3,17] To derive these relationships, the authors have compiled reservoir performance data from 31 CO_2-EOR sites in the continental US. Based on the annual rates of CO_2 + H_2O injection, of which schedule was adapted from the literature,[22] oil, CO_2, and water flows were iteratively estimated for each year of operation in minimum, average, and maximum oil recovery cases. Inputs of the technical model are given in Table S1.

Oil production from CO_2-EOR can be accurately estimated by finite difference models (ECLIPSE, GEM/STARS, etc.), which require a large amount of data about the selected field and a long simulation time. Without access to historical production data of past CO_2-EOR projects, previous techno-economic models of CO_2-EOR were limited to rule-of-thumb[11] and semi-analytical[13] methods of oil production modeling. It has been known that the semi-analytical flow of the previous models neglected important reservoir mechanisms such as miscible displacement and CO_2 solubility in oil and thus underestimated the CO_2 storage potential of CO_2-EOR.[14] Oil production in reservoir performance data was fitted in the log-logistic, which was used to identify incremental oil recovery in our model.[17] Incremental oil recovery is the amount of oil produced during EOR, and its calculations are given in Table S2. Fitted model parameters for the incremental oil recovery are given in Table S3. The volume of CO_2 needed for producing one barrel of incremental oil is called the CO_2 utilization factor.[22] Net CO_2 utilization factor is a volume of newly purchased CO_2 per barrel of produced incremental oil up to that time, which was identified by a two-parameters asymptotic formula.[17]

After CO_2 was injected into injection wells, it broke through in production wells. The produced CO_2 was separated from other reservoir fluids and compressed and re-injected along with newly purchased CO_2 from the power plant (Figure 1). A substantial part of the injected CO_2 was stuck in rock pores and did not reach recycling equipment. The industry uses metrics called “CO_2 retention” that represents the non-recycled portion of the injected CO_2.[16] It needs to be noticed that CO_2 retention is different from CO_2 storage. Unlike pure CO_2 storage, CO_2-EOR brings back CO_2 to the surface, recycles, and injects it back numerous times where almost 50% of CO_2 is retained (or does not reach the recycling loop) in the reservoir, and the other half breaks through in the production wells.[16] However, nearly all purchased CO_2 (>95%) was stored in the reservoir at the end of CO_2-EOR.[17] Such a distinction between CO_2 retention and CO_2 storage is crucial, as it might lead to confusion when discussing the sustainability of CO_2-

EOR.[3] Calculations related to CO_2 are given in Table S4. Compressed CO_2 was injected into an oil reservoir in the WAG process, where it was periodically altered with water (brine). Brine calculations and relevant coefficients are given in Tables S5 and S6.

LCA Method. We have estimated potential GHG emissions of CO_2-EOR in major hydrocarbon provinces of the world and compared them with actual average GHG emissions from all oil types produced in the country. Hereinafter, we refer to oil derived from CO_2-EOR and average production methods as "CO_2-EOR oil" and "average oil", respectively.

The goal of this LCA is to estimate potential GHG emissions of CO_2-EOR in different countries, where CO_2 could be sourced from coal or natural gas-fired power plants. LCA of CO_2-EOR oil is based on earlier works of US-based institutes.[3,4,6] Figure 2 illustrates the upstream (UP), gate-to-gate (GG), and downstream (Down) segments of LCA covered in our work, where EOR is just one segment of a complex system with two final products: oil and electricity.

The functional unit of LCA is normalized to 1 bbl of crude oil, where 3.5% of carbon content remains in noncombustible oil products. Inputs of the LCA model are given in Table S7. Detailed descriptions of each segment are given in Section 3 of the Supporting Information (parameters and assumptions are found in Tables S8−S13). Due to the limited geography of CO_2-EOR, the US CO_2-EOR reservoir database was used in the LCA of all countries.[17] Thus, we are assuming the same geologic conditions and same operating strategy of CO_2-EOR in the gate-to-gate segment of all hydrocarbon provinces.

Combining GHG emissions from three segments and adding both subsurface ($\text{Loss}_{\text{subsufr}}$) and surface-related ($\text{Loss}_{\text{surf}}$) losses results in total GHG emissions (EF_{total}) of CO_2-EOR (eq 1).

$$EF_{\text{total}} = UP + GG + Down + \text{Loss}_{\text{subsurf}} + \text{Loss}_{\text{surf}} \quad (1)$$

As CO_2 is sourced from a coal or gas-fired power plant, the CO_2-EOR LCA boundary has two products, that is, oil and electricity produced at the power plant with a CO_2 capture unit. GHG emissions of the LCA boundary should be properly apportioned between the products of our CO_2-EOR system to avoid double counting of carbon credits.[4] Carbon credits of CO_2 storage in the CO_2-EOR system can only belong to the power plant operator or oil field operator. In other words, the CO_2-EOR system cannot result in both low-carbon electricity and low-carbon oil.[23]

The carbon credits have been estimated by applying system expansion.[3,4,6,24] The low-carbon electricity from a power plant with a CO_2 capture unit displaced conventional electricity with high-carbon intensity and thus offsets the total GHG emissions in the LCA boundary. In our case, electricity displacement is an amount of generated electricity by the low-carbon power source to meet the CO_2 demand of the CO_2-EOR oil field. The source of displaced conventional electricity is unknown. Therefore, we used the average GHG emission factor of the country's electricity grid. We assume 100% of displacement credits go to the oil, offsetting its total GHG emissions. Subtracting GHG emission savings due to the displacement (Displ) of conventional electricity from total GHG emissions resulted in a net GHG emission factor (EF_{net}) of CO_2-EOR (eq 2).

$$EF_{\text{net}} = EF_{\text{total}} - \text{Displ} \quad (2)$$

Using a similar LCA system, average oil GHG emissions were estimated individually for each country covered in our study, where we used recent country-specific GHG emission factors for exploration, drilling, development, production, surface processing, and transport to the refinery inlet and refinery operations.[25,26] GHG emission factors of average oil from refined oil transport and combustion were assumed to be the same as in CO_2-EOR oil. More details are provided in Section 3.4 of the Supporting Information.

Economic Model. The economic model can estimate the feasibility of investment decisions of CO_2-EOR projects based on the net present value (NPV) and oil production cost (OPC) of the project (Table S26). The economic model relies on discounted cash flow analysis that contains six components, that is, capital expenditure (Capex), CO_2 feedstock, other operational expenses (Opex), revenue, tax, and carbon trading (Figure S1). It was assumed that the CO_2-EOR project would be carried out for 25 years (2015−2039). For the demonstration purposes of the model, the economic model was adapted to Kazakhstan's market conditions. Inputs of the economic model are given in Table S17.

The Capex of the CO_2-EOR project in this study is an initial investment required for modifying existing infrastructure and developing additional infrastructure for the oil field experiencing production decline after waterflooding (Table S18). Launching CO_2-EOR as a tertiary recovery involves a new CO_2 recycling unit, upsizing production facilities, workover of existing wells, and a small number of new wells.[13] The Capex model was developed based on the research works by McCoy, Dahowski et al., and Wei et al.[13,14,27] The Capex components are converted from 2004 US cost to 2015 Kazakhstan cost using cost index coefficients of IHS Markit and oil and gas cost data of Rystad Energy given in Tables S20 and S21 of Supporting Information, respectively.[28,29]

Unlike previous studies, our study considered the CO_2 feedstock in CO_2-EOR as a separate cost component of discounted cash flow analysis. Other Opex included operation and maintenance (O&M) cost of well fields, CO_2 compression cost, water compression, fluid lifting, CO_2 recycling cost, and monitoring and verification cost (Table S22). Opex unit costs are given in Table S23. The revenue of CO_2-EOR came from the annual sales of crude oil production, where the average oil production cost in the country was taken as 46 USD/bbl (Table S24).[30] It was subject to various taxes incorporated in the economic model based on the upstream tax rules of Kazakhstan outlined in the "On Subsoil and Subsoil Use" document.[31] The overall tax rate was estimated to be around 35%.

Kazakhstan has adopted Emission Trading System (ETS) in 2013 to regulate GHG emissions.[32] As of 2020, Kazakhstan ETS has 225 participants, and it operates based on the "cap-and-trade" principle, where the government sets "cap" (allowance) of GHG emissions to the participants and they "trade" with allowances to cover their GHG emission demands. The allowances were determined based on the national benchmark of GHG emissions for oil production, which is 476 kg CO_2 eq/bbl.[33] In CO_2-EOR, we assume carbon credits of electricity displacement were traded as GHG allowance in the carbon market among the regulated sectors. Currently, the GHG allowance price is around 1 USD/t CO_2 eq[32]

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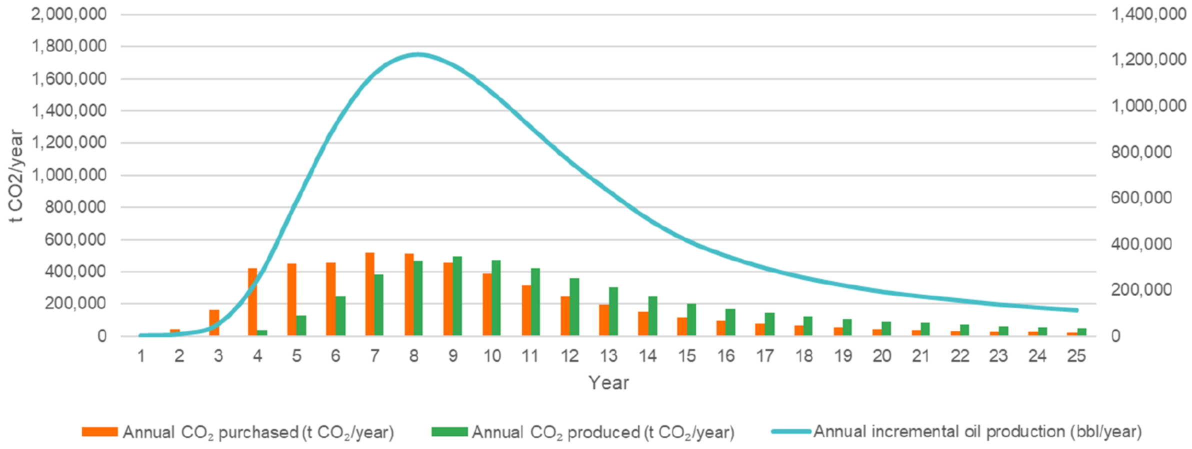

Figure 3. Annual oil and CO_2 flows in the CO_2-EOR project (average oil recovery case).

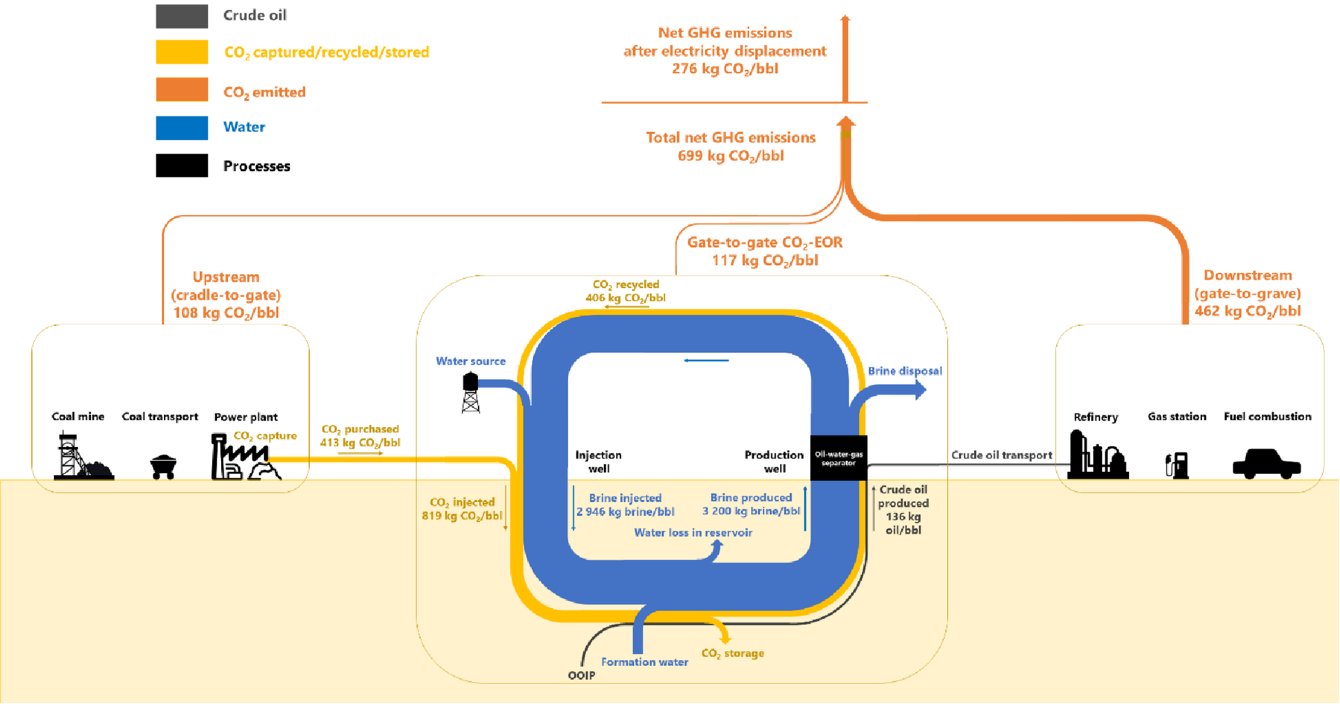

Figure 4. Sankey diagram of fluid balance in CO_2-EOR in Kazakhstan for the average oil recovery case. The functional unit of the diagram is the kg fluid/bbl oil produced. (* minor surface and subsurface CO_2 losses are not shown in the Sankey diagram.)

■ RESULTS AND DISCUSSION

Technical Model Results. The oil production by average oil recovery was estimated as 11.7%, and the net CO_2 utilization rate was 7.96 mscf/bbl for oil field with 100 MMbbl original oil in place (OOIP). As the oil recovery changed to low (4.41%) and high (24.15%) values, the net CO_2 utilization rate changed to 9.49 and 7.51 mscf CO_2/bbl, respectively (Table S25 in the Supporting Information). The log-logistic function for the incremental oil recovery rate is depicted in Figure 3, which shows the only tertiary stage of production after the primary and secondary (waterflooding) stages of the EOR. Annual production reached a peak of 1.2 MMbbl/year in 8 years (Figure 3). The model results here are based on US CO_2-EOR, which historically optimized their production to increase oil recovery,[34] but reservoir performance may change when optimizing CO_2 storage to target CO_2 credits.

The gross CO_2 utilization rate in the CO_2-EOR was 15.77 mscf/bbl, composed of a net CO_2 utilization rate of 7.96 and a CO_2 recycle rate of 7.81 mscf/bbl. Both annual purchased and recycled CO_2 rates changed similarly to the annual production rate with a relatively faster increase followed by a gradual decline. The peak demand for the purchased and recycled CO_2 occurred in the 7th (519 kt CO_2/year) and 9th year (497 kt CO_2/year), respectively. As the project matured, the annual use of recycled CO_2 surpassed the purchased CO_2 (Figure 3). Such changes in the CO_2 utilization can be explained by a gradual decline in CO_2 retention over the lifetime of the project, indicating that less CO_2 was retained in the reservoir and more CO_2 broke through in production wells with time. High recycle rates of CO_2 decreased the need for purchased CO_2 coming from the industrial source, and thus the net CO_2 utilization factor decreased. Similar behavior in CO_2 utilization was confirmed by previous industry experience, supporting a similar trend in purchased and recycled CO_2 use.[16]

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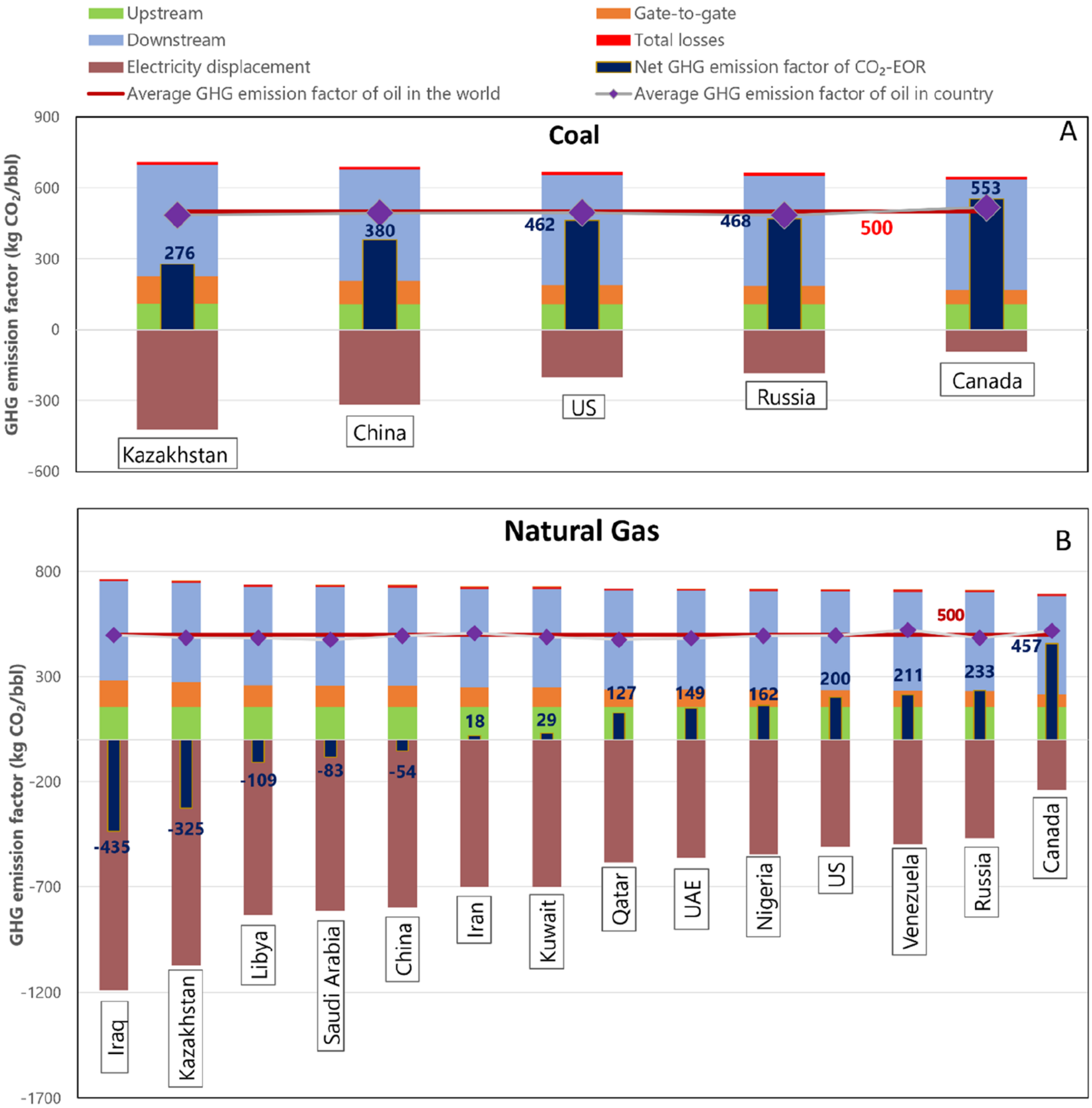

Figure 5. Life cycle GHG emissions of CO_2-EOR in countries with the largest hydrocarbon reserves [(A) coal is an electricity source; (B) natural gas is an electricity source].

The production rate of water in CO_2-EOR was significantly higher than that of crude oil and CO_2 (Figure 4). The industry describes the ratio of injected water to the injected solvent (CO_2) with the "WAG ratio", which uses reservoir volumes of water and CO_2.[35] WAG ratio in our modeled process is 3.7, which agrees well with values reported in the EOR literature.[36]

LCA Results. Figure 4 shows the flow of CO_2, oil, and water in the life cycle of CO_2-EOR in Kazakhstan. Although injected CO_2 continuously broke through in production wells during the production stage, most purchased CO_2 remained in the geological formation when the CO_2-EOR project was completed. The mass balance of CO_2-EOR showed that GHG emissions of CO_2-EOR mostly came from the downstream segment (462 kg CO_2 eq/bbl), where refined crude oil was burnt in a combustion engine (Figure 4). The contributions of upstream and gate-to-gate segments to the LCA of CO_2-EOR were relatively small, that is, 108 and 117 kg CO_2 eq/bbl, respectively. Adding 2 and 10 kg CO_2 eq/bbl due to surface and subsurface losses to three segments resulted in total GHG emissions of 699 kg CO_2 eq/bbl. Further subtracting 423 kg CO_2 eq/bbl due to electricity displacement resulted in a net life cycle GHG emission of 276 kg CO_2 eq/bbl (Figure 4).

We used the LCA model to assess the sustainability of CO_2-EOR in 14 countries with the largest hydrocarbon reserves (Figure 5).[37] As previously noted, total GHG emissions of upstream, gate-to-gate, and downstream segments were offset by the electricity displacement. Two factors—GHG emission factor of the electricity grid and type of fuel used in power plants mainly governed the displacement credits of CO_2-EOR.

Switching from the coal-fired power plant to a natural gas-fired power plant required more electricity to be generated to cover the same CO2 demand from the oil field. Such a trend is due to the low-carbon intensity of natural gas compared to coal. Thus, countries where electricity is generated by natural gas had high electricity displacement values than countries using coal, which ultimately resulted in low (Iran, Kuwait,

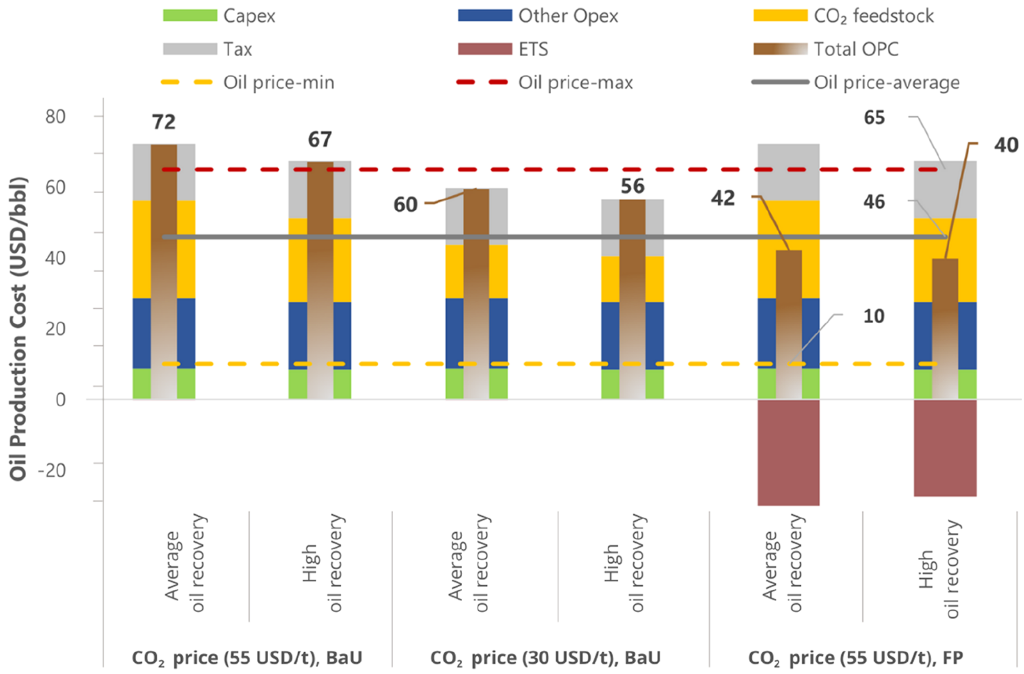

Figure 6. Variation of OPC in Kazakhstan with oil recovery, CO_2 cost, and policy conditions (CO_2 prices of 55 USD/t and 30 USD/t are for coal-fired power plants and other facilities with low CO_2 capture cost, respectively).

Qatar, UAE, etc.) or even negative (Iraq, Kazakhstan, Libya, Saudi Arabia, and China) GHG emission factors of CO_2-EOR oil (Figure 5). Negative emissions in CO_2-EOR do not mean CO_2 removal from the atmosphere, but rather an avoidance of CO_2 emissions. Capturing low-concentration CO_2 gas at the stack of NGCC power plants incurs high energy demands and high costs of up to \$100/t CO_2.[38] Absent specific policy mechanisms or other investment criteria of NGCC power plants eliminate them from being the first CO_2 source targets for CO_2-EOR. Coal-fired power plants, on the other hand, have lower costs of CO_2 capture than NGCC. Although coal resulted in relatively lower electricity displacement, it still can provide low net GHG emission factors of CO_2-EOR in Kazakhstan, China, US, and Russia (276−468 kg CO_2 eq/bbl range), which are less than GHG emission factors of average oil produced in countries (483−517 kg CO_2 eq/bbl range) (Figure 5).

The magnitude of electricity displacement credits was also dictated by the GHG emission factor in the country's electricity grid. Kazakhstan and China have the highest GHG emission factors of their electricity grids, yielding the greatest electricity displacement values among coal-user countries. Iraq, Kazakhstan, Libya, Saudi Arabia, and China had the same trend in the natural gas category (Figure 5). Conversely, US, Russia, and Canada had the lower GHG emission factor of the electricity grid; thus, their net GHG emission factors of CO_2-EOR emissions were the highest (462−553 kg CO_2 eq/bbl range) (Figure 5). Although we expect high net GHG emissions of CO_2-EOR in the US, Russia, and Canada, separate oil fields can still benefit from large electricity displacement given that they are displacing electricity sources with greater GHG emission factors, such as coal-fired power plants. Thus, our ranking is not a definitive or exhaustive list of global GHG emissions for CO_2-EOR. Instead, it intends to show an overall picture of CO_2-EOR sustainability in the largest hydrocarbon provinces of the world.

Economic Analysis Results. Kazakhstan has diverse industrial CO_2 emitters. More than half of the industrial GHG emissions in the country come from power plants for the generation of electricity and heat energy, using coal as a primary source.[20] The cost of CO_2 capture in coal combustion processes is 41−51 USD/t CO_2.[38] The common basic cost of CO_2 transportation via a 250 km onshore pipeline was estimated by the USDOE method as 4.9 USD/t CO_2.[39] Assuming that coal-burning power plants will be the main target of CO_2 capture projects, we used 55 USD/t CO_2 for the combined cost of CO_2 capture and transportation in our simulations.

The economic analysis considered two scenarios of oil recovery categorized by the average and high ranges, and the two scenarios of policy cases classified as Business As Usual (BaU) and Favorable Policies (FP). FP indicated the BaU carbon credit change from 1 to 150 USD/t CO_2. Figure 6 shows the cost of producing one barrel of oil in six scenarios compared with the average oil production cost (OPC) in the Kazakhstan oil market. As of 2020, the average OPC in the country was ~46 USD/bbl[30] and varied from 10 (minimum) to 65 USD/bbl (maximum).[40] When CO_2 was sourced from the coal-fired power plants under BaU scenarios, the estimated OPC of CO_2-EOR in average recovery and high recovery oil fields were 72 and 67 USD/bbl, exceeding the average market OPC by 57 and 46%, respectively. CO_2 feedstock, other Opex, and tax were significant contributors of the OPC with shares of 35−38, 28, and 22−24%, respectively. Industry experience also suggested that the CO_2 feedstock was the most expensive component of the CO_2-EOR economy.[16]

The cost of the CO_2 feedstock can be lowered as the CO_2 concentration increases in the gas stream and thus alleviates the separation cost of CO_2. A higher CO_2 concentration could be found in non-combustion industrial emission processes (chemical reactions) than combustion emission processes (most fuel combustions).[38] Ammonia processing and steel and

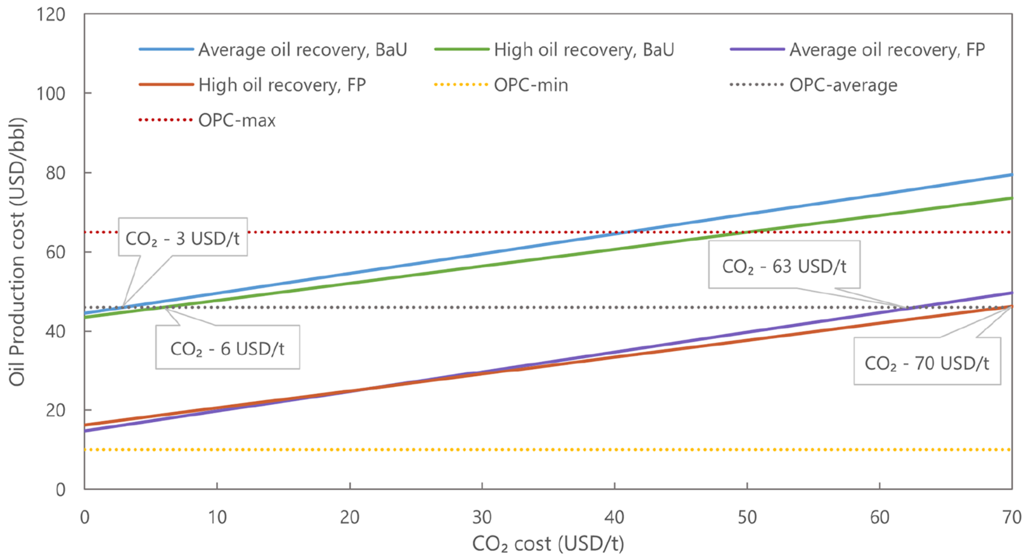

Figure 7. Breakeven cost of feedstock CO_2 for average and high oil recovery cases.

iron production plants have high purity CO_2 emission processes. Thus, they have relatively low CO_2 capture costs varying between 14 and 35 USD/t CO_2.[38] Both industries exist in Kazakhstan, and they can provide a low cost for CO_2 capture projects. The combined cost of low-cost CO_2 capture and transportation projects was assumed to be 30 USD/t CO_2. The OPC of CO_2-EOR projects with average and high oil recoveries was estimated to be 60 and 56 USD/bbl (Figure 6), respectively, as the CO_2 originated from low-cost CO_2 capture sources. Both values were lower than the maximum OPC that can be encountered in the Kazakhstan oil and gas market. With current market conditions, CO_2-EOR in the oil fields can compete with expensive oil production methods used in Kazakhstan, given that CO_2 is sourced from its process emissions (not combustion emissions) of industry.

Under the carbon credit price by the FP scenario (150 USD/t CO_2), the OPC of the average oil recovery was 42 USD/bbl, which is lower than the average OPC of Kazakhstan. The high oil recovery case could decrease it further down to 40 USD/bbl, also lower than the average OPC of Kazakhstan (Figure 6). Carbon credits earned by electricity displacement can greatly help the economy of CO_2-EOR given that favorable conditions exist in carbon markets.

Although Kazakhstan has now a high GHG emission factor of the electricity grid (900 kg CO_2/MWh), it will decrease in the future as decarbonization measures step in. Decarbonization of electricity will shrink displacement credits of CO_2-EOR over time, thus carbon credits of CO_2-EOR are time-dependent. Such phenomena are already taking place in the US, where electricity generation has been shifting from coal to natural gas in the last few decades.[41] Our estimation showed higher net GHG emissions for CO_2-EOR when sourcing CO_2 from the coal-fired power plant (462 vs 438 kg CO_2 eq/bbl) compared to the earlier LCA study.[3] Switching CO_2 sources from coal-fired power plants to natural gas power plants can still allow CO_2-EOR operators to have large electricity displacements, which can benefit from governmental carbon subsidies (e.g., Section 45Q in the US).[42] Effect of power plant configuration and fuel types on CO_2-EOR emissions are explored in Section 3.5 of the Supporting Information (Figure S3). Other variances in both technical (e.g., geologic conditions, well productivity) and economic (e.g., price volatility in energy markets) parameters also cause uncertainty in the results of our study. Thus, relevant uncertainty analysis of TEA was provided in Section 6 of the Supporting Information (Figure S4).

Figure 7 shows the breakeven price of feedstock CO_2 to equal the average OPC (46 USD/bbl) in the Kazakhstan oil and gas market. Under the BaU scenario, the breakeven costs of the feedstock CO_2 were 3 and 6 USD/t CO_2 for average and high oil recovery cases. Introducing carbon credits of 150 USD/t CO_2 in the FP scenario increased a purchased CO_2 breakeven cost to 63 and 70 USD/t CO_2 for both cases. The techno-economic assessment results indicated that the OPC from CO_2-EOR could be decreased by developing low-cost CO_2 capture technologies and leveraging policy instruments such as carbon pricing in ETS.

IMPLICATIONS

The sustainability aspect of CO_2-EOR has been explored globally in major hydrocarbon provinces of the world using cradle-to-grave LCA. We have apportioned the environmental credits between the main product (oil) and coproduct (electricity) of the CO_2-EOR system in line with the guidance of ISO 14040 to handle multifunctionality such that the functional unit can be a single product—1 bbl of crude oil. LCA results showed that, when sourcing CO_2 from coal-fired power plants, Kazakhstan could benefit most from carbon credits of CO_2-EOR, with China, US, and Russia being other candidates. All other hydrocarbon provinces with natural gas used in electricity could benefit from low-emission CO_2-EOR as well. However, their CO_2-EOR potential will be challenged by energy-intensive CO_2 capture units of NGCC power plants.

The study also provided a better quantitative understanding of the CO_2-EOR economy using the newly developed TEA model of CO_2-EOR, which has two distinct advantages from previous models:

1 TEA model incorporated one of the most extensive industrial statistical data sets of CO_2-EOR available in peer-reviewed literature studies. The model enhanced by the field data provided valuable insights into the long-term economic performance of the CO_2-EOR.

2 TEA was integrated with the LCA of CO_2-EOR, which can estimate the carbon credits.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acs.est.1c06834.

Modeling description including the background information with the organization of TEA and LCA for CO_2-EOR; technical model information with crude oil calculations, CO_2 calculations, water equations, inputs, and model parameters; LCA information with LCA boundaries of CO_2-EOR, LCA inputs, input parameters, equations, and LCA results by countries and fuel type; economic model information with model inputs and equations; summary of reservoir performance data from US CO_2-EOR data set for low, average, and high oil recovery cases; techno-economic model output equations; and sensitivity of OPC by model parameters (PDF)

CO_2-EOR Excel model and LCA results (ZIP)

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Notes

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■ REFERENCES

(1) Kolster, C.; Masnadi, M. S.; Krevor, S.; Mac Dowell, N.; Brandt, A. R. CO_2 enhanced oil recovery: a catalyst for gigatonne-scale carbon capture and storage deployment? *Energy Environ. Sci.* **2017**, *10*, 2594−2608.

(2) NETL. *An Assessment of Gate-To-Gate Environmental Life Cycle Performance of Water-Alternating-Gas CO_2-Enhanced Oil Recovery in the Permian Basin*, 2010.

(3) Azzolina, N. A.; Peck, W. D.; Hamling, J. A.; Gorecki, C. D.; Ayash, S. C.; Doll, T. E.; Nakles, D. V.; Melzer, L. S. How green is my oil? A detailed look at greenhouse gas accounting for CO_2-enhanced oil recovery (CO2-EOR) sites. *Int. J. Greenh. Gas Control* **2016**, *51*, 369−379.

(4) Jaramillo, P.; Griffin, W. M.; Mccoy, S. T. Life Cycle Inventory of CO_2 in an Enhanced Oil Recovery System. *Environ. Sci. Technol.* **2009**, *43*, 8027−8032.

(5) NETL. *Gate-to-Gate Life Cycle Inventory and Model of CO_2-Enhanced Oil Recovery*, 2013.

(6) Cooney, G.; Littlefield, J.; Marriott, J.; Skone, T. J. Evaluating the Climate Benefits of CO_2-Enhanced Oil Recovery Using Life Cycle Analysis. *Environ. Sci. Technol.* **2015**, *49*, 7491−7500.

(7) Nuñez-Lopez, V.; Gil-Egui, R.; Hosseininoosheri, P.; Hovorka, S. D.; Lake, L. W. *Carbon Life Cycle Analysis of CO_2-EOR for Net Carbon Negative Oil (NCNO) Classification (Final Report)*; University of Texas, 2019; Vol. *412*.

(8) Dipietro, P.; Balash, P.; Wallace, M. A Note on Sources of CO_2 Supply for Enhanced Oil Recovery Operations. *Society of Petroleum Engineers*; NETL, 2012, November 2011, pp 14−17.

(9) Buli, N.; Abnett, K.; Twidale, S. EU Carbon Price Hits Record 50 Euros Per Tonne on Route to Climate Target. Reuters. 2021, https://www.reuters.com/business/energy/eu-carbon-price-tops-50-euros-first-time-2021-05-04/ (accessed Dec 18, 2021).

(10) Holtz, M. H.; Nance, P. K.; Finley, R. J. Reduction of Greenhouse Gas Emissions through CO_2-EOR in Texas. *Environ. Geosci.* **2001**, *8*, 187−199.

(11) Bock, B.; Rhudy, R.; Herzog, H. J.; Klett, M.; Davison, J.; Simbeck, D. *Economic Evaluation of CO_2 Storage and Sink Enhancement Options*; Tennessee Valley Authority, 2003, pp 1−476.

(12) ARI. *Basin Oriented Strategies for CO_2-Enhanced Oil Recovery—Permian Basin*; Prepared for U.S. Department of Energy, 2006.

(13) McCoy, S. T. The Economics of CO_2 Transport by Pipeline and Storage in Saline Aquifers and Oil Reservoirs, Sean T McCoy A Thesis Submitted in Partial Fulfillment of the Requirements for the Degree of Doctor of Philosophy, Engineering & Public Policy Carnegie Mellon, 2008.

(14) Wei, N.; Li, X.; Dahowski, R. T.; Davidson, C. L.; Liu, S.; Zha, Y. Economic evaluation on CO_2-EOR of onshore oil fields in China. *Int. J. Greenh. Gas Control* **2015**, *37*, 170−181.

(15) Jiang, J.; Rui, Z.; Hazlett, R.; Lu, J. An integrated technical-economic model for evaluating CO_2 enhanced oil recovery development. *Appl. Energy* **2019**, *247*, 190−211.

(16) Melzer, L. S. Carbon Dioxide Enhanced Oil Recovery (CO_2-EOR): Factors Involved in Adding Carbon Capture, Utilization and Storage (CCUS) to Enhanced Oil Recovery. 2012.

(17) Azzolina, N. A.; Nakles, D. V.; Gorecki, C. D.; Peck, W. D.; Ayash, S. C.; Melzer, L. S.; Chatterjee, S. CO_2 storage associated with CO_2 enhanced oil recovery: A statistical analysis of historical operations. *Int. J. Greenh. Gas Control* **2015**, *37*, 384−397.

(18) *World Bank. CO2 emissions (metric tons per capita)*, 2018.

(19) US EIA. Kazakhstan 2017 Primary Energy Data in Quadrillion Btu. https://www.eia.gov/international/overview/country/KAZ (accessed Dec 18, 2021).

(20) Abuov, Y.; Seisenbayev, N.; Lee, W. CO_2 storage potential in sedimentary basins of Kazakhstan. *Int. J. Greenh. Gas Control* **2020**, *103*, 103186.

(21) Seisenbayev, N.; Abuov, Y.; Tolenbekova, Z.; Lee, W. *Assessment of CO_2-EOR and its Geo-Storage Potential in Oil Reservoirs of Precaspian Basin*; European Geophysical Union: Kazakhstan, 2020; Vol. *2020*.

(22) Bachu, S. Identification of oil reservoirs suitable for CO_2 -EOR and CO_2 storage (CCUS) using reserves databases, with application to Alberta, Canada. *Int. J. Greenh. Gas Control* **2016**, *44*, 152−165.

(23) IEA. Can CO_2-EOR Really Provide Carbon-Negative oil? https://www.iea.org/commentaries/can-co2-eor-really-provide-carbon-negative-oil (accessedDec 18, 2021).

(24) ISO. *ISO 14040 Environmental Management—Life Cycle Assessment—Principles and Framework*, 1997; Vol. *1997*.

(25) Masnadi, M. S.; El-Houjeiri, H. M.; Schunack, D.; Li, Y.; Englander, J. G.; Badahdah, A.; Monfort, J.-C.; Anderson, J. E.; Wallington, T. J.; Bergerson, J. A.; Gordon, D.; Koomey, J.; Przesmitzki, S.; Azevedo, I. L.; Bi, X. T.; Duffy, J. E.; Heath, G. A.; Keoleian, G. A.; McGlade, C.; Meehan, D. N.; Yeh, S.; You, F.; Wang, M.; Brandt, A. R. Global Carbon Intensity of Crude Oil Production. *Science* **2018**, *361*, 851−853.

(26) Jing, L.; El-Houjeiri, H. M.; Monfort, J.-C.; Brandt, A. R.; Masnadi, M. S.; Gordon, D.; Bergerson, J. A. Carbon Intensity of Global Crude Oil Refining and Mitigation Potential. *Nat. Clim. Change* **2020**, *10*, 526−532.

(27) Dahowski, R. T.; Davidson, C. L.; Li, X. C.; Wei, N. A $70/$tCO_2$ greenhouse gas mitigation backstop for China's industrial and electric power sectors: Insights from a comprehensive CCS cost curve. *Int. J. Greenh. Gas Control* **2012**, *11*, 73−85.

(28) IHS_Markit. Costs and Technology Indexes. https://ihsmarkit.com/Info/cera/ihsindexes/index.html (accessed Dec 18, 2021).

(29) Rystad_Energy. Rystad Energy on CNN Money. https://money.cnn.com/interactive/economy/the-cost-to-produce-a-barrel-of-oil/index.html (accessed Dec 18, 2021).

(30) Forbes.kz. Average Onshore Oil Production Cost in Kazakhstan. https://forbes.kz//massmedia/ubyitochnyie_barreli_srednyaya_sebestoimost_kazahstanskoy_nefti_-_46/? (accessed Dec 18, 2021).

(31) Ministry of Justice of the Republic of Kazakhstan. On Subsoil and Subsoil Use. https://adilet.zan.kz/eng/docs/K1700000125 (accessed Dec 19, 2021).

(32) International Carbon Action Partnership. *Kazakhstan Emissions Trading Scheme*, 2020. No. September.

(33) Ministry of Ecology Geology and Natural Resources. On Approval of the List of Benchmarks in Regulated Sectors of the Economy. https://adilet.zan.kz/rus/docs/V2100023621 (accessed Dec 29, 2021).

(34) Jessen, K.; Kovscek, A. R.; Orr, F. M. Increasing CO_2 storage in oil recovery. *Energy Convers. Manag.* **2005**, *46*, 293−311.

(35) Juanes, R.; Blunt, M. J. Impact of Viscous Fingering on the Prediction of Optimum WAG Ratio. *SPE J.* **2007**, *12*, 486−495.

(36) Christensen, J. R.; Stenby, E. H.; Skauge, A. Review of WAG Field Experience. *SPE Reservoir Eval. Eng.* **2001**, *4*, 97−106.

(37) US EIA. Crude Oil Including Lease Condensate Reserves. 2020, https://www.eia.gov/international/rankings/world?pa=106&u=0&f=A&v=none&y=01%2F01%2F2020&ev=false (accessed Dec 20, 2021).

(38) Bains, P.; Psarras, P.; Wilcox, J. CO_2 capture from the industry sector. *Prog. Energy Combust. Sci.* **2017**, *63*, 146−172.

(39) Rubin, E. S.; Davison, J. E.; Herzog, H. J. The cost of CO_2 capture and storage. *Int. J. Greenh. Gas Control* **2015**, *40*, 378−400.

(40) Kapital.kz. Oil Production Cost in Kazakhstan. https://kapital.kz/economic/85335/nurlan-nogayev-rasskazal-o-sebestoimosti-kazakhstanskoy-nefti.html (accessed Dec 20, 2021).

(41) IEA United States. https://www.iea.org/countries/united-states (accessed Feb 19, 2022).

(42) Anderson, J. J.; Rode, D.; Zhai, H.; Fischbeck, P. A Techno-Economic Assessment of Carbon-Sequestration Tax Incentives in the U.S. Power Sector. *Int. J. Greenh. Gas Control* **2021**, *111*, 103450.