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Gate-to-Gate Life Cycle Assessment of CO_2 Utilisation in Enhanced Oil Recovery: Sustainability and Environmental Impacts in Dukhan Field, Qatar

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ABSTRACT

This study presents a gate-to-gate Life Cycle Assessment (LCA) evaluating the sustainability and environmental impacts of utilising CO_2 for Enhanced Oil Recovery (EOR) in Dukhan Field. The assessment employs a detailed model that encompasses CO_2 capturing, transportation, injection, and oil production processes. Utilising Gabi software, the study assesses CO_2 emissions across different stages of the EOR process and evaluates the environmental efficiency using two functional units: '1 kg of CO_2 captured' and '1 kg of oil produced'. Results indicate that Post-Combustion Capture (PCC) contributes the highest emissions, accounting for 76% of the total Global Warming Potential (GWP), while transportation pipelines and separators contribute only 2% and 4%, respectively. By Year 21, emissions drop by over 98%, with a corresponding GWP reduction from 4.73 billion $kgCO_2e$ in Year 1 to 94.97 million $kgCO_2e$. Emission rates for CO_2 capture and oil production also decrease significantly, reaching 0.01 $kgCO_2e$ per kg of CO_2 captured and 0.03 $kgCO_2e$ per kg of oil produced. These findings highlight the transformative potential of closed-loop CO_2 management, where recycling reduces reliance on external CO_2 sources and enhances the sustainability of EOR operations. This study provides actionable insights for optimising CO_2-EOR systems, contributing to both economic and environmental sustainability goals.

Keywords: Life Cycle Analysis, Carbon Dioxide, Carbon Capture, Optimisation, Environment.

INTRODUCTION

Global CO_2 emissions have risen significantly, reaching 37.9 Gt in 2018, contributing over 75% of total greenhouse gases (International Energy Agency, 2023). The oil and gas sector alone accounts for 10% of these emissions (Kamkeng et al., 2021). Carbon Capture and Utilisation (CCU) is a promising approach to mitigating these emissions by capturing CO_2 and repurposing it for Enhanced Oil Recovery (EOR).

The environmental performance of CCU technologies has been widely evaluated in literature through the Life Cycle Assessment (LCA); a holistic approach that examines both resource consumption and pollutant release across all phases of a product's life cycle (Faber et al., 2022). Building on established LCA frameworks, Müller et al., (2020) introduced guidelines tailored to CCU in collaboration with over 40 experts, aiming to quantify the environmental benefits of CCU products and processes relative to conventional fossil-based alternatives. One key challenge when applying LCA to CCU arises from its multifunctional nature: CO_2 serves both as a waste product and a valuable resource. This dual role creates a direct link between CO_2 emission sources and its subsequent use in CCU, making the assessment more complex. To address this, the guidelines recommend a systematic approach aligned with ISO 14040/44 standards, which involves segmenting the process, expanding the assessment scope, and allocating impacts based on chemical or physical criteria. This methodology helps navigate the complexities introduced by CCU's multifunctionality.

Several studies have critically evaluated CO_2-EOR using LCA, highlighting both its potential and limitations as a carbon sequestration strategy. Jaramillo et al. (2009) examined lifecycle emissions from CO_2 capture at power plants through to the combustion of the produced oil, questioning CO_2-EOR's net benefits for carbon sequestration. In contrast, Jensen et al. (2018) compared CO_2 EOR with conventional oil and natural gas production, illustrating that CO_2 EOR could reduce lifecycle greenhouse gas emissions, with outcomes heavily influenced by factors such as CO_2 capture rate and oil recovery efficiency.

Morgan et al. (2021) conducted a gate-to-gate LCA over a decade of CO_2-EOR operations, using 100% anthropogenic CO_2. The study demonstrated that CO_2-EOR has the potential to achieve net-negative emissions, citing a 92% storage rate for injected CO_2 and identifying operational improvements as key to enhancing environmental outcomes.

Similarly, Abuov et al. (2022)'s study indicated that CO_2-EOR can yield lower GHG emissions than conventional oil production, particularly under favorable carbon pricing and when CO_2 is sourced from coal-fired or NGCC power plants, thereby maintaining economic viability while reducing emissions.

Despite extensive research on CO_2-EOR, most studies focus on short-term assessments of CO_2 capture, injection, and sequestration, with limited analysis of long-term environmental performance. The transition from external CO_2 supply to a closed-loop recycling system remains underexplored, particularly in oil reservoirs in Qatar, such as the Dukhan Field.

Existing evaluations do not comprehensively quantify the long-term emissions reduction potential, sequestration efficiency, or overall sustainability of such systems. A systematic, long-term assessment of CO_2-EOR operations is essential to address this gap, providing critical insights into emissions dynamics, sequestration effectiveness, and the feasibility of achieving a self-sustaining carbon management approach.

Study Objectives

This study aims to fill that gap by focusing on a detailed, gate-to-gate LCA that examines the environmental impacts of direct CO_2 injection for oil recovery, offering new insights into emissions reductions over an extended timeline. It also evaluates the operational efficiency of CO_2 sequestration under specific conditions unique to Dukhan Field, thereby contributing to a more targeted understanding of EOR's sustainability potential. To achieve this, the objectives of this research are to:

- Evaluate the environmental impacts of direct CO_2 injection for EOR using LCA.
- Quantify emissions and environmental efficiencies through two functional units: '1 kg of CO_2 captured' and '1 kg of oil produced.'
- Simulate operational efficiency and emissions reductions over 21 years, transitioning from external CO_2 to recycled CO_2.
- Analyse the feasibility of closed-loop CO_2 management in achieving long-term emissions reductions of over 90%.
- Provide recommendations to policymakers and industry leaders for implementing sustainable CO_2-EOR practices.

METHODOLOGY

Building on the CO_2 reinjection closed-loop model developed by (Sawaly et al., 2022) for Dukhan Field, this study evaluates the feasibility and environmental impact of direct CO_2 injection for Enhanced Oil Recovery (EOR) in Dukhan Field, Qatar, without prior water injection. Initially, the model depends on externally sourced CO_2 but progressively transitions to recycling recovered CO_2 from previous cycles, with the potential to operate solely on reinjected CO_2 by the 21st year (Figure 1).

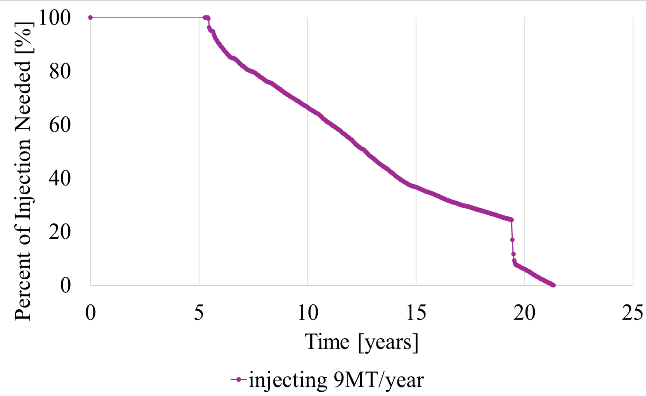

Figure 1: CO_2 utilisation process with reinjection.

Model description

This gate-to-gate Life Cycle Assessment (LCA) examines the CO_2-EOR process from capture through oil production, excluding downstream refining and end-of-life emissions. Gabi software is used for environmental impact assessment, quantifying emissions and energy use. The system boundary extends from the flue gas stream exiting the source to crude oil production, incorporating CO_2 capture, compression, transportation, injection, separation, and reinjection to form a closed-loop system. The field specifications and production rate over time are detailed in (Sawaly et al., 2022). The model simulates a progressive transition from externally sourced CO_2 to internally recycled CO_2 over the 21-year period. As CO_2 recycling efficiency increases, the need for additional CO_2 purchases declines, and the production rate is adjusted dynamically based on reservoir performance and injection efficiency. The CO_2 composition of the produced stream is also accounted for through changes in

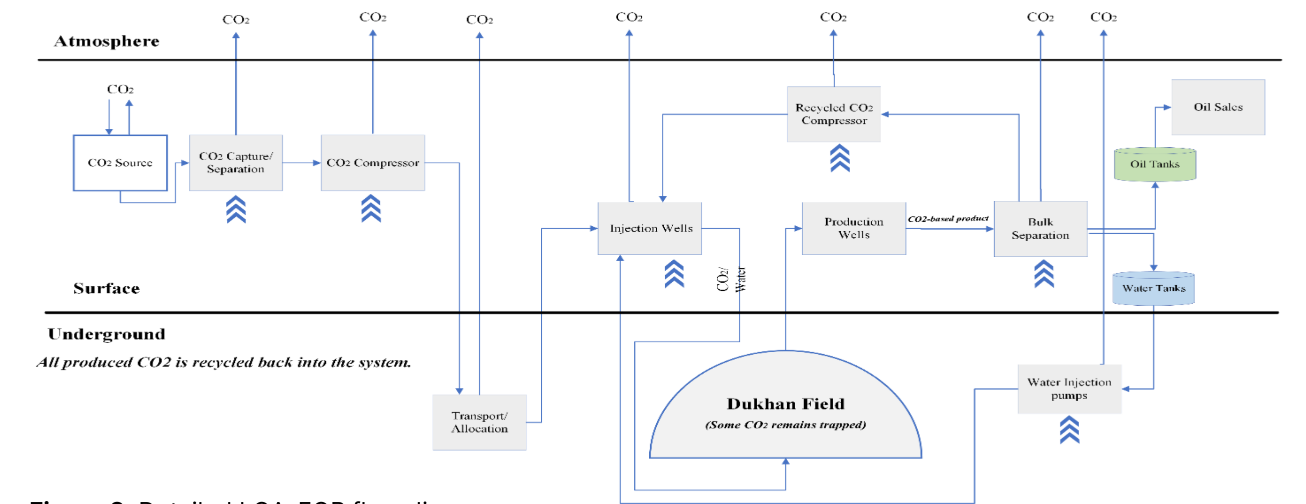

Figure 2: Detailed LCA-EOR flow diagram.

Table 1: Key operational and environmental metrics.

Category	Term	Value	Unit	Reference
Operational Metrics	Feed Flowrate	9000000	t/y	(Sawaly et al., 2023)
	Production Rate	0.2	tonOil/tonCO_2	(Sawaly et al., 2023)
	Distance	100	km	(Sawaly et al., 2023)
Energy Metrics	Capture	3.32	GJ/tonCO_2	(Azzolina et al., 2017)
	Compression and transportation *(pipeline, 100km)*	1.3	kWh/tonCO_2	(Azzolina et al., 2017)
	Injection Well	64.5	kWh/tonCO_2	(Azzolina et al., 2017)
	Uplift (pump) production	20	kWh/bbl of oil	(Azzolina et al., 2017)

separation efficiency and reinjection rates over time. These dynamic changes are integrated into the model to reflect realistic long-term operational scenarios.

Two functional units are used: '1 kg of CO_2 captured', assessing emissions per unit of injected CO_2, and '1 kg of oil produced', quantifying the carbon footprint of recovered oil. As illustrated in Figure 2, CO_2 is initially captured and purified at the source, compressed, and transported to injection wells, where it enhances oil recovery while storing CO_2 underground. During production, CO_2 resurfaces with oil and water, is separated, recompressed, and reinjected, minimising reliance on fresh CO_2 and maximising sustainability and efficiency. This approach supports a low-carbon oil recovery strategy, demonstrating the long-term potential of EOR as an emissions-reduction solution.

Available data and assumptions

This section outlines the key operational and environmental parameters used to simulate the Enhanced Oil Recovery (EOR) process and assess its environmental impacts. These parameters include CO_2 capture emissions, energy consumption during capture, transportation, and injection, as well as CO_2 production rates and oil recovery yields.

CO_2 is captured using amine-based Post-Combustion Capture (PCC) technology with a 90% purity assumption, ensuring less than 10% impurities for efficient processing. The capture process requires both electricity and heat—electricity powers pumps and mechanical components, while heat regenerates the amine solvents in a desorption cycle, allowing solvent reuse and improving process sustainability. Emissions at this stage include direct emissions from PCC operations and indirect emissions linked to energy consumption, depending on the carbon intensity of the power source.

After capture and purification, CO_2 is transported via pipeline to the EOR site, requiring electricity-powered pumps to maintain flow and pressure. This ensures efficient delivery while minimising pressure losses. Emissions stem from pump and compressor operations, as well as energy consumption associated with transport. At the Dukhan Field, CO_2 is injected directly into the reservoir to enhance oil recovery, displacing hydrocarbons and reducing viscosity. This stage requires electricity to power injection pumps, as well as energy for drilling and completing wells. Emissions at this phase include direct emissions from drilling operations and indirect emissions from power consumption. Oil extraction involves drilling and well operations, requiring energy to operate lifting

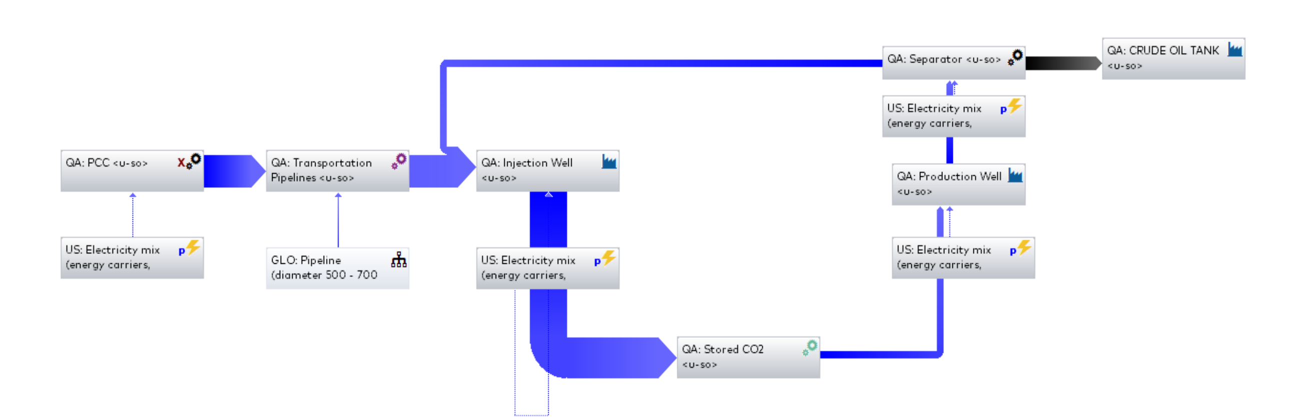

Figure 3: Gabi Screenshot of the model.

systems and production pumps. Emissions from this stage stem from both direct drilling activities and indirect energy use. Post-production, CO_2 is separated from oil and water using thermal and mechanical processes, requiring heat for thermal separation and electricity for compression and mechanical separation. Recovered CO_2 is then recompressed and reinjected, minimising the need for additional CO_2 purchases and supporting a closed-loop EOR system. Emissions include direct emissions from separation and indirect emissions from energy use. The emissions for each stage were calculated by multiplying the energy consumed at that stage by the CO_2-intensity factor for Qatar's electricity generation, which is primarily based on natural gas. The CO_2 intensity of Qatar's electricity grid is approximately 0.111 tCO_2/GJ (or ~0.40 tCO_2/MWh)(IEA, 2019). This value represents the emissions released per unit of power generated in a natural gas system. In the case of pipeline transportation, a direct emission factor of 0.0001986 t CO_2/t CO_2 transported (per 100 km) is applied, as reported by Azzolina et al. (2017). This value reflects fugitive or operational emissions—such as small leaks and routine venting—rather than emissions from the electricity used to operate pumps or compressors.

The methodology acknowledges that brine is excluded from the analysis due to a lack of specific data, which is a recognised limitation of the current LCA scope. Table 1 summarises the key operational and environmental metrics, providing essential data for assessing the sustainability and efficiency of CO_2-EOR in Dukhan Field.

RESULTS AND DISCUSSION

This section presents the key findings from the gate-to-gate LCA of the CO_2-EOR process in Dukhan Field. The analysis evaluates the environmental and operational impacts of CO_2 injection, focusing on enhanced oil recovery, reduced emissions, and the benefits of closed-loop recycling to support optimisation and sustainable development.

The LCA provides a detailed assessment of various operational scenarios over several years. The system boundaries extend from CO_2 extraction from the flue gas stream to oil production, excluding the life cycle impacts of crude oil products and upstream LNG production. Figure 3 illustrates the model employed in this assessment, highlighting the interactions between key variables and processes involved in CO_2-EOR.

Figure 4 presents a breakdown of the Global Warming Potential (GWP) across different stages of the CO_2-EOR process, offering critical insights into environmental performance. The stages include the injection well, post-combustion capture (PCC), the separator, transportation pipelines, and the total cumulative impact. The chart also shows the emission rates per kilogram of CO_2 captured and per kilogram of oil produced, providing a comprehensive view of the environmental footprint at each stage.

The PCC stage is the most emission-intensive, with a GWP of 1.20 billion $kgCO_2e$, highlighting the high energy demand of CO_2 capture, particularly when powered by non-renewable sources. In contrast, the injection well demonstrates a relatively low GWP of 0.29 billion $kgCO_2e$, indicating efficient CO_2 utilisation in oil recovery with minimal contribution to overall emissions. Emissions from the separator and transportation pipelines are significantly lower, at 0.07 billion $kgCO_2e$ and 0.02 billion $kgCO_2e$, respectively, reflecting effective management of these processes to minimise environmental impact. The total GWP across all stages is 1.58 billion $kgCO_2e$, with emission rates of 0.53 $kgCO_2e$ per kilogram of oil produced. This underscores the challenge of managing emissions throughout the CO_2-EOR process while identifying PCC as a critical area for potential improvement to reduce overall emissions.

Figure 5 illustrates the evolution of CO_2 utilisation and its impact on environmental performance over time through four distinct scenarios, each representing different stages of the CO_2-EOR process at Dukhan Field. These scenarios, spanning from Year 1 to Year 21, demonstrate the shift from external CO_2 sourcing to increased internal recycling. Each scenario reflects varying proportions of CO_2 sourced from external versus internally recycled CO_2, highlighting the system's progression toward greater sustainability and efficiency. The gradual reduction in CO_2 allocation from external sources, combined with increased recycling and reinjection of CO_2 produced during oil extraction, emerges as a pivotal factor in enhancing the environmental and operational performance of the entire process.

As shown in Figure 5, in Year 1, when 100% of the required CO_2 is sourced externally, the system exhibits a high Global Warming Potential (GWP) of 4.73 billion $kgCO_2e$, reflecting the substantial environmental impact associated with early reliance on external CO_2 sources. However, as internal recycling mechanisms are adopted, the need for external CO_2 supply diminishes progressively. By Year 21, when no CO_2 is sourced externally, the GWP drops to 94.97 million $kgCO_2e$, representing a reduction of over 98% compared to Year 1. This decline underscores the success of the closed-loop CO_2 management strategy, wherein most of the CO_2 required for EOR operations is derived from recycled sources. Consequently, the emission rates per kilogram of CO_2 captured and per kilogram of oil produced decrease to 0.01 $kgCO_2e$ and 0.03 $kgCO_2e$, respectively, further demonstrating the efficiency gains achieved through internal CO_2 recycling.

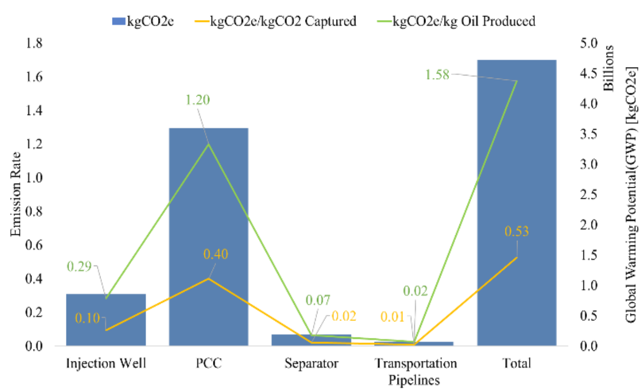

Figure 4: GWP of the base case scenario (year 1).

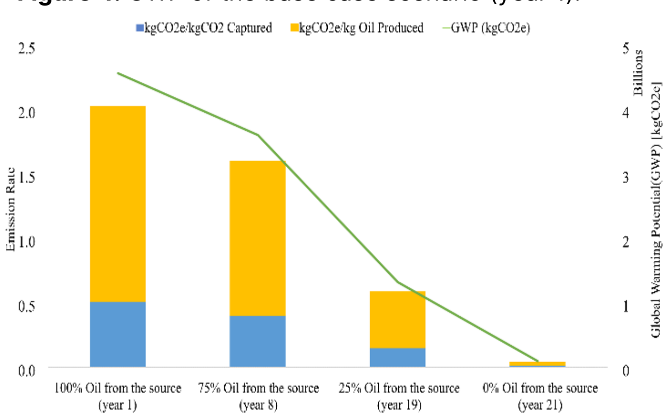

Figure 5: Comparison of 3 GWP Scenarios for 4 different years.

By improving CO_2 utilisation and reducing reliance on external supply, the system enhances oil production while simultaneously lowering emissions, thereby optimising the need for additional CO_2 input and improving the overall carbon efficiency of the EOR process. The reduction in PCC-related emissions over time reinforces the broader environmental benefits of transitioning towards a more self-sustaining CO_2-EOR operation. Overall, the results highlight the significant potential of internal CO_2 recycling to enhance the sustainability and environmental performance of CO_2-EOR operations. By reducing reliance on external CO_2 sources and optimising internal recycling processes, the system achieves substantial reductions in emissions while supporting a more economically viable and environmentally responsible oil recovery process.

The findings of this study align closely with those of previous CO_2-EOR LCA studies. Nuñez-López et al. (2017) reported an emission rate of 2.7 $kgCO_2e$ per kilogram of oil produced, which is consistent with the overall trend observed in this analysis. Slight variations may stem from differences in reservoir properties, energy sources, and operational conditions. Despite these variations, both studies underscore the potential of CO_2-EOR to enhance oil recovery while managing environmental impacts.

CONCLUSION

This This study presents a detailed gate-to-gate Life Cycle Assessment (LCA) of CO_2 utilisation in Enhanced Oil Recovery (EOR) at Dukhan Field, Qatar, demonstrating the environmental and operational benefits of direct CO_2 injection without water flooding. The results show that implementing internal CO_2 recycling can reduce net emissions by over 90% by Year 21, confirming the effectiveness of closed-loop CO_2 management in cutting the carbon footprint of EOR operations. This reduction is primarily driven by the progressive replacement of externally sourced CO_2 with recycled CO_2, decreasing reliance on external carbon inputs.

The analysis evaluates CO_2 capture, transportation, injection, and recycling using functional units ("1 kg of CO_2 captured" and "1 kg of oil produced") to provide objective performance benchmarks. The findings underscore that Post-Combustion Capture (PCC) is the most emission-intensive stage, contributing approximately 76% of the total Global Warming Potential (GWP) in Year 1. Improving PCC energy efficiency and exploring alternative capture technologies, such as membrane-based systems or cryogenic separation, could significantly reduce the overall carbon footprint of CO_2-EOR.

While the findings highlight the potential of CO_2-EOR in reducing emissions and enhancing oil recovery, the study's scope is limited to the specific geological and operational characteristics of Dukhan Field. This may restrict the direct applicability of the results to other fields with different reservoir conditions. Future research should extend the system boundaries to include downstream emissions from refining and combustion and assess the impact of CO_2 purity and reservoir pressure on sequestration efficiency and oil recovery rates. Comparative studies across different reservoir profiles would strengthen the generalisability of these findings.

The demonstrated reduction in emissions through internal CO_2 recycling also enhances economic feasibility by lowering the need for external CO_2 supply. This reinforces the strategic role of CO_2-EOR in supporting a transition toward low-carbon oil production, providing a viable path for balancing energy security with environmental responsibility.

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