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Advancing Atmospheric CO_2 Capture Integration with Oil Reservoir Injection for Sustainable Domestic Hydrocarbon Production Expansion

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Abstract

The escalating threat of climate change, driven primarily by anthropogenic carbon dioxide (CO_2) emissions, has intensified global efforts to identify and implement sustainable carbon management strategies. Among these, the integration of atmospheric CO_2 capture with enhanced oil recovery (EOR) in geological formations such as depleted oil reservoirs presents a promising dual-benefit approach. This strategy not only contributes to long-term CO_2 sequestration but also supports domestic hydrocarbon production through improved oil recovery efficiency. By leveraging existing infrastructure and reservoir knowledge, atmospheric CO_2 injection into oil fields offers an economically viable pathway for reducing carbon footprints while extending the productive lifespan of mature reservoirs. This synergy between environmental stewardship and energy security is particularly critical for nations striving to meet both climate goals and growing energy demands. Moreover, this approach aligns with the global transition toward low-carbon energy systems by transforming traditional fossil fuel operations into carbon-mitigating processes. The potential to scale and optimize this integration could significantly reshape national energy portfolios, promoting sustainability without compromising energy independence. This paper explores the evolving nexus between atmospheric CO_2 capture technologies and oil reservoir injection, highlighting the environmental, economic, and energy security implications of this innovative approach for sustainable domestic hydrocarbon production expansion in the 21st century.

Keywords: *Carbon Dioxide Capture, Oil Reservoir Injection, Enhanced Oil Recovery (EOR), Sustainable Hydrocarbon Production, Carbon Sequestration.*

I. INTRODUCTION

➢ *The Global Challenge of CO_2 Emissions and Climate Change*

The persistent rise in atmospheric carbon dioxide (CO_2) concentrations represents a defining environmental challenge of the 21st century. With global CO_2 levels surpassing 420 ppm in recent years, climate-related disruptions such as extreme weather events, rising sea levels, and ecological imbalances have become more frequent and severe. Fossil fuel combustion remains the leading contributor to these emissions, particularly from power generation, transportation, and industrial sectors (Bui et al., 2018). Addressing this challenge necessitates both reducing emissions at their source and developing long-term carbon management strategies such as CO_2 capture, utilization, and storage (CCUS). Integration of atmospheric CO_2 capture with oil reservoir injection offers a dual solution mitigating environmental impact while enabling energy resource recovery (Okoh et al., 2024).

The alignment of CO_2 capture with enhanced oil recovery (EOR) strategies provides not only a method of long-term sequestration but also supports sustainable hydrocarbon production, especially in oil-dependent economies. Countries like the United States and China have successfully piloted projects where captured CO_2 is injected into depleted oil fields to extract residual oil while sequestering carbon underground (Saeidi et al., 2020). This approach exemplifies how atmospheric CO_2 capture can be strategically redirected from being a liability to becoming a resource, positioning it as a vital component in climate change mitigation and energy transition frameworks.

➢ *Need for Sustainable Domestic Hydrocarbon Strategies*

As global energy systems pivot toward decarbonization, oil-producing nations are under increasing pressure to adopt sustainable domestic hydrocarbon strategies that align with environmental goals while safeguarding energy security. In this evolving context, carbon capture and storage (CCS) integrated with hydrocarbon recovery offers a technologically feasible pathway to mitigate emissions without halting production. This synergy enables countries to meet climate targets while maximizing the economic value of existing petroleum assets (Hosseini &Lashkaripour, 2021). Particularly in nations heavily reliant on fossil fuel revenues, such as Nigeria, Saudi Arabia, and parts of Latin America, developing sustainable production models is not just strategic but imperative for long-term energy and economic resilience (Okoh et al., 2024).

The Injection of captured atmospheric CO_2 into mature reservoirs represents an advanced form of enhanced oil recovery (EOR) that contributes both to reducing carbon intensity and revitalizing domestic oil fields. According to Zhou et al. (2020), future hydrocarbon strategies must integrate climate-aligned technologies such as CO_2-EOR to remain viable within stringent regulatory and market-driven carbon constraints. Moreover, such approaches support the diversification of energy portfolios while utilizing domestic infrastructure. This positions sustainable hydrocarbon development as a bridge between conventional fossil energy systems and a low-carbon future, emphasizing innovation over abandonment.

➢ *Objectives and Scope of CO_2-EOR Integration*

The primary objective of CO_2-EOR (Carbon Dioxide-Enhanced Oil Recovery) integration is to simultaneously enhance oil recovery from mature or depleted reservoirs while permanently storing atmospheric CO_2 underground. This dual-purpose strategy is designed to align hydrocarbon production with global climate goals by transforming oil extraction into a more environmentally responsible process. CO_2-EOR serves not only as a tool for prolonging the economic life of domestic oil fields but also as a critical mechanism for mitigating greenhouse gas emissions through geological sequestration. By using captured atmospheric CO_2 as an injection fluid, operators can improve reservoir pressure, increase oil displacement efficiency, and contribute to carbon neutrality goals.

The scope of CO_2-EOR integration extends across technical, economic, and environmental dimensions. Technically, it involves the deployment of advanced injection systems, monitoring protocols, and reservoir management techniques to ensure optimal recovery and safe CO_2 storage. Economically, it leverages existing oil field infrastructure, reducing capital expenditures and increasing return on investment. Environmentally, it facilitates the transition toward low-carbon energy systems by offering a scalable and immediate solution for CO_2 reduction. This integrative framework is especially valuable in carbon-intensive economies seeking to reconcile fossil fuel utilization with sustainable development priorities, marking a significant evolution in hydrocarbon resource management.

➢ *Structure of the Paper*

This paper is systematically organized into seven core sections to provide a comprehensive exploration of atmospheric CO_2 capture and its integration with Enhanced Oil Recovery (EOR). Section 1 introduces the background, motivation, objectives, scope, and structure of the study. Section 2 reviews the scientific and technological foundations of atmospheric CO_2 capture and EOR, including recent advancements. Section 3 delves into the methodology used for evaluating the integration of these systems. Section 4 presents the findings, highlighting key results from case studies and simulations. Section 5 discusses the implications of these findings in terms of energy security, emissions reduction, and economic feasibility. Section 6 critically evaluates policy alignment, regulatory environments, and public perception challenges. Finally, Section 7 outlines future directions, including integration with renewable energy systems, technological innovations, and global scalability strategies. This structured approach ensures clarity, coherence, and a logical flow of arguments throughout the paper.

II. ATMOSPHERIC CO_2 CAPTURE TECHNOLOGIES

➢ *Direct Air Capture (DAC) and Its Evolution*

Direct Air Capture (DAC) has emerged as a frontier technology in climate mitigation, targeting the removal of CO_2 directly from ambient air regardless of emission sources. Unlike traditional point-source carbon capture systems, DAC systems are uniquely flexible and location-independent, enabling deployment near geological storage sites or utilization hubs as presented in figure 1 (Okoh et al., 2024). Early DAC technologies faced substantial challenges related to energy intensity and high operational costs. However, recent advancements in sorbent materials, process integration, and modular design have significantly improved energy efficiency and economic feasibility. These improvements have allowed DAC to transition from a conceptual framework to pilot and commercial-scale operations, with plants in Iceland, the United States, and Canada already demonstrating functional models.

The evolution of DAC Is now closely tied to its role in integrated carbon management strategies such as CO_2-EOR. As atmospheric CO_2 becomes a viable feedstock for enhanced oil recovery, DAC systems must meet stringent purity, scalability, and cost requirements. Integration into the hydrocarbon sector is facilitated by hybrid systems combining DAC with renewable energy inputs and thermal management innovations. These developments enhance CO_2 delivery for injection while reducing lifecycle emissions. The alignment of DAC with subsurface utilization, particularly in oil reservoir injection, is redefining its role from niche application to a strategic pillar in sustainable energy transitions.

Figure 1 illustrates the operational mechanism of Direct Air Capture (DAC), a rapidly evolving technology designed to combat climate change by removing carbon dioxide (CO_2) directly from the atmosphere. In its evolving form, DAC uses large fans to draw in ambient air (Step 1), which is then passed through a chemical filter typically an amine-based adsorbent that selectively captures CO_2 molecules (Step 2). The remaining clean air is released back into the environment (Step 3), while the isolated CO_2 is either sequestered underground or repurposed for industrial use, such as in concrete or synthetic fuels (Step 4). This process signifies a major advancement in carbon management, offering scalable, modular, and increasingly cost-effective solutions aligned with global climate mitigation strategies. As DAC technology matures, its integration into national carbon neutrality goals and circular carbon economies becomes increasingly vital.

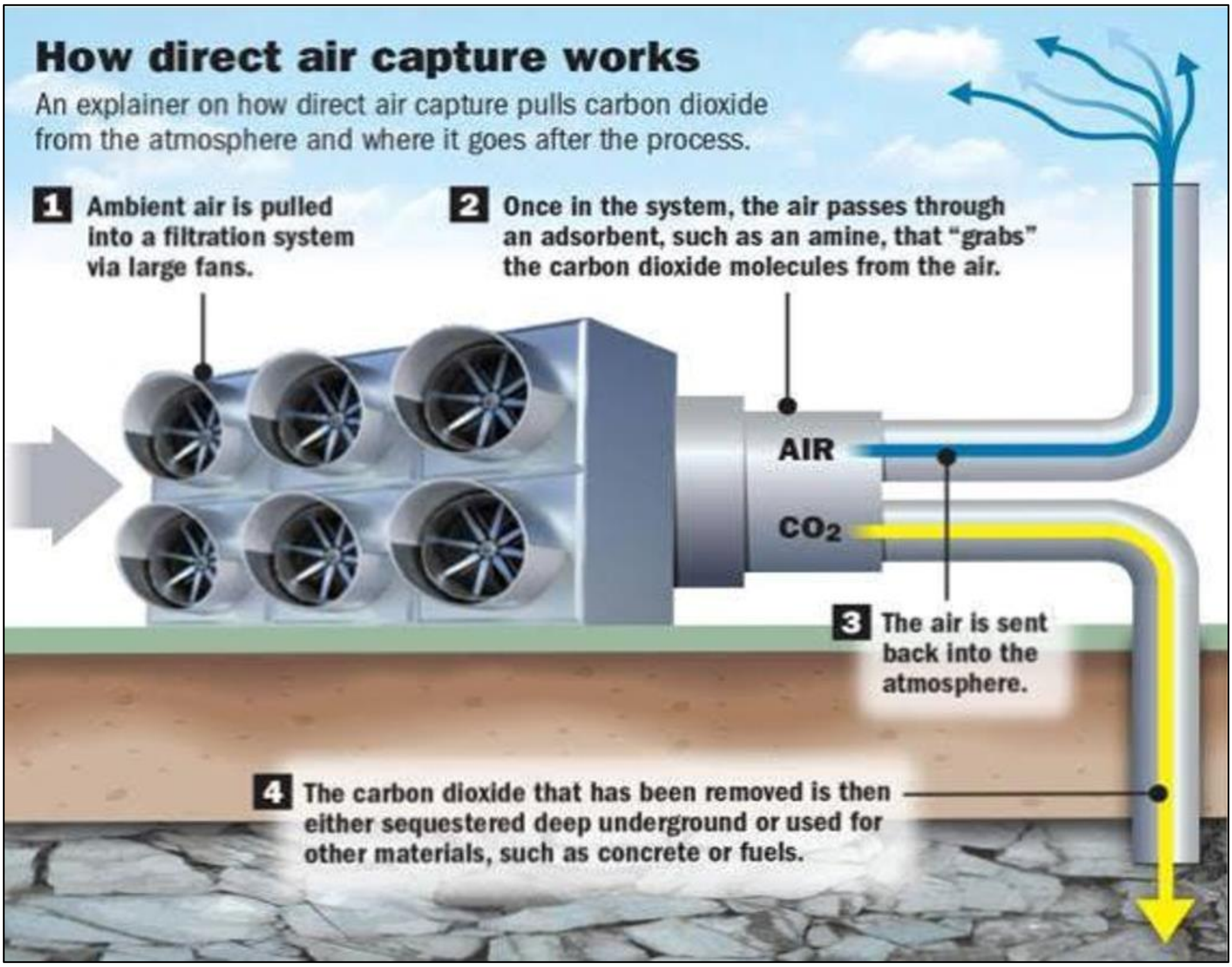

Fig 1 Picture of Capturing Carbon from Thin Air: The Process and Promise of Direct Air Capture (DAC) (Fuhrman et al., 2021).

- *Efficiency and Cost of CO_2 Capture Systems*

The efficiency and cost of CO_2 capture systems are central to their scalability and integration within industrial and energy sectors, particularly in applications such as enhanced oil recovery. Technological advances in sorbent materials, contactor design, and thermal regeneration have increased CO_2 capture efficiency to over 90% in optimized systems. Sorbent-based direct air capture units, for example, have achieved significant reductions in energy requirements, especially through low-temperature regeneration cycles as represented in table 1 (Okoh et al., 2024). These gains in performance are critical in minimizing the overall energy penalty associated with CO_2 separation, compression, and transport. Additionally, innovations in solid amine-based and metal-organic framework sorbents continue to push the limits of selective CO_2 adsorption under varying atmospheric conditions.

Despite these advancements, cost remains a major barrier to large-scale deployment. Current estimates place the cost of direct air capture between $100 and $600 per ton of CO_2 removed, depending on technology type, energy source, and site-specific factors (Azarabadi & Lackner, 2021; Fuhrman et al., 2021). However, coupling CO_2 capture with economic utilization pathways such as injection into oil reservoirs can partially offset operational expenses through revenue from enhanced hydrocarbon recovery. Such integrative strategies are essential for making CO_2 capture both commercially viable and environmentally impactful in the near term (Imoh, 2023).

Table 1 Summary of Efficiency and Cost of CO_2 Capture Systems

Capture Technology	CO_2 Capture Efficiency (%)	Cost per Ton of CO_2 Captured (USD)	Remarks
Post-Combustion Capture	85–90%	40–80	Widely used in power plants; retrofit potential is high but energy-intensive.
Pre-Combustion Capture	90–95%	30–60	High efficiency in IGCC systems; not suitable for retrofitting existing plants.
Oxy-Fuel Combustion	90–95%	60–100	Requires pure oxygen supply; higher cost but suitable for new builds.
Direct Air Capture (DAC)	50–75%	100–600	Flexible in location; currently expensive but improving with tech innovation.

➢ *Role of Renewable Energy in CO_2 Capture*

The integration of renewable energy sources into CO_2 capture systems is becoming increasingly vital for reducing the carbon footprint and operational costs associated with these technologies. Renewable energy especially solar and wind offers a clean and decentralized power supply capable of meeting the thermal and electrical demands of energy-intensive capture processes. For instance, solar thermal energy can be harnessed for regenerating chemical sorbents, while photovoltaic systems can supply electricity to operate vacuum pumps and fans in direct air capture units. This synergy enables CO_2 capture systems to become more sustainable, flexible, and geographically deployable, especially in off-grid or resource-constrained environments (Okoh et al., 2024).

Beyond environmental benefits, the coupling of renewables with CO_2 capture enhances the overall techno-economic viability of large-scale deployment. Studies have shown that renewable-powered systems can significantly reduce lifecycle emissions and make capture operations more consistent with net-zero targets (Sodiq et al., 2022; Wang et al., 2021). Furthermore, renewable integration helps to stabilize energy input costs, which are typically volatile when reliant on fossil-based grids. These advantages are particularly important for CO_2 capture applications tied to oil reservoir injection, where uninterrupted operation is crucial. Leveraging renewables thus supports the dual mandate of climate mitigation and domestic hydrocarbon productivity by ensuring carbon capture systems are both clean and continuous (Ijiga et al., 2024).

III. OIL RESERVOIR INJECTION TECHNIQUES

➢ *Fundamentals of CO_2-Based Enhanced Oil Recovery (EOR)*

CO_2-based Enhanced Oil Recovery (EOR) is a tertiary recovery technique that injects carbon dioxide into mature or depleted oil reservoirs to increase extraction efficiency. When CO_2 is introduced under high-pressure conditions, it becomes miscible with crude oil, reducing the oil's viscosity and interfacial tension as presented in figure 2 (Ijiga et al., 2023). This miscibility enhances oil mobility and facilitates its flow toward production wells, thereby improving overall recovery rates. The injected CO_2 also acts to repressurize the reservoir, further boosting production in formations that have undergone pressure decline. This process is particularly effective in sandstone and carbonate reservoirs with light to medium oil compositions, which are conducive to miscibility conditions (Idika et al., 2024).

Beyond enhancing recovery, CO_2-EOR presents an avenue for permanent CO_2 storage, making it a promising strategy for combining hydrocarbon production with climate change mitigation. Injected CO_2 that is not produced back with the oil remains trapped within the reservoir through structural, residual, and solubility trapping mechanisms (Al-Menhali et al., 2022; Zendehboudi et al., 2021). This dual functionality transforms oil fields into both energy and carbon management assets. Furthermore, the adaptability of CO_2-EOR to integrate with atmospheric carbon capture technologies supports its inclusion in national decarbonization plans. It reflects a strategic convergence of fossil fuel optimization and environmental stewardship.

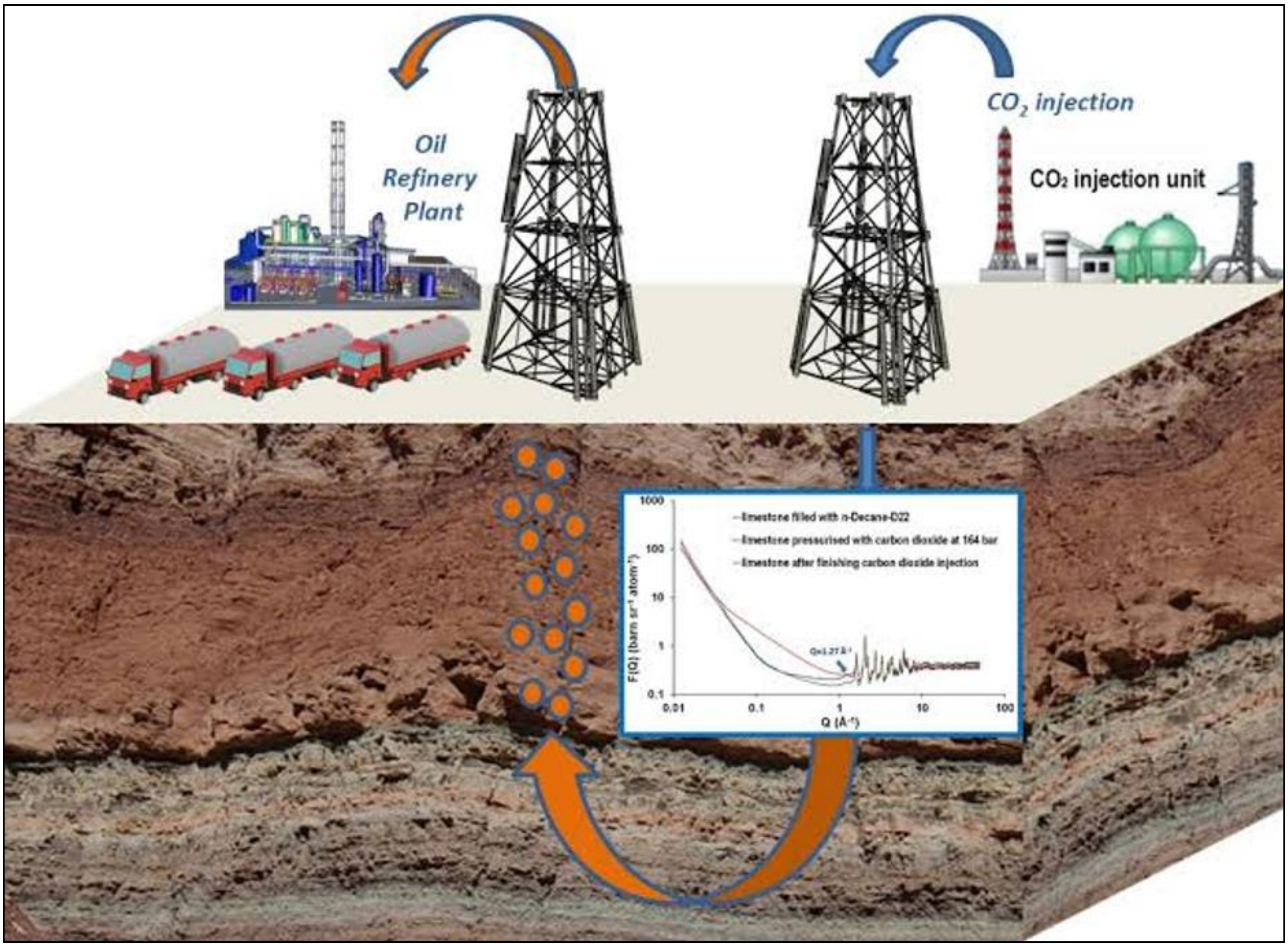

Fig 2 Picture of CO_2-Enhanced Oil Recovery: Boosting Extraction and Sequestering Carbon (Al-Menhali et al., 2022).

Figure 2 The image illustrates the fundamental process of CO_2-based Enhanced Oil Recovery (EOR), which involves capturing carbon dioxide from industrial sources like oil refineries and injecting it into mature oil reservoirs to improve oil extraction. The CO_2 injection increases the pressure within the reservoir and reduces the viscosity of the trapped oil, making it easier to extract. This process is depicted by the CO_2 injection unit channeling CO_2 into underground rock formations, where it interacts with the existing oil and geological structures, as shown by the chart of physical changes in limestone due to CO_2 exposure. The dual benefit of this method is evident it not only boosts oil recovery from declining fields but also provides a means for long-term carbon sequestration, contributing to climate change mitigation.

- *Selection Criteria for Reservoir Suitability*

The effectiveness of CO_2-based Enhanced Oil Recovery (EOR) depends heavily on the selection of geologically and operationally suitable reservoirs. Several key factors guide this evaluation, including reservoir depth, temperature, pressure, porosity, and permeability. Optimal reservoirs typically exceed a depth of 800 meters to maintain CO_2 in a supercritical state, which enhances miscibility with crude oil and ensures better mobility (Ijiga et al., 2021). Additionally, high porosity and permeability are essential for facilitating fluid flow and maximizing contact between injected CO_2 and trapped hydrocarbons. Lithology also plays a critical role, with sandstone and carbonate formations offering favorable conditions due to their structural and mineralogical characteristics.

Reservoir heterogeneity, fluid properties, and caprock integrity further influence suitability for CO_2 injection and long-term containment. A competent caprock is necessary to prevent upward migration and ensure permanent CO_2 sequestration. Economic feasibility, proximity to CO_2 sources, and existing infrastructure are also considered in comprehensive site screening (Fosbøl et al., 2022; Kim et al., 2021). Advanced modeling tools and reservoir simulation software are increasingly used to assess these variables and optimize selection criteria. Choosing the right reservoir not only improves EOR performance but also aligns with environmental goals, reinforcing the value of integrated carbon capture and storage systems (Ijiga et al., 2022).

- *Geomechanical and Chemical Interactions During Injection*

The injection of CO_2 into subsurface oil reservoirs initiates a complex array of geomechanical and chemical interactions that influence both enhanced oil recovery efficiency and long-term reservoir stability. Geomechanically, the increase in pore pressure during injection alters the in-situ stress regime, potentially causing reservoir deformation, fault reactivation, or caprock fracturing if not properly managed. These responses must be accurately modeled to ensure that the injection does not compromise structural integrity or induce seismicity. Reservoirs with pre-existing fractures or fault zones require particular attention, as stress redistribution could result in unwanted CO_2 migration pathways as represented in table 2 (Karacan & Goodarzi, 2021).

Chemically, CO_2 reacts with reservoir fluids and rock minerals, leading to dissolution and precipitation reactions that alter porosity and permeability. In carbonate-rich formations, CO_2 dissolution forms carbonic acid, which can enhance dissolution of calcite, increasing porosity and injectivity in the short term (Ijiga et al., 2021). However, secondary mineral precipitation may reduce flow paths over time. Such reactive transport processes also influence pH, brine composition, and metal mobilization, requiring sophisticated geochemical modeling for accurate prediction and mitigation (Gaus et al., 2022). Understanding these interactions is vital for designing safe and efficient CO_2-EOR operations, ensuring both hydrocarbon recovery and secure geological sequestration.

Table 2 Summary of Geomechanical and Chemical Interactions During Injection

Interaction Type	Description	Potential Risks	Monitoring/Management Strategy
Rock Deformation	Changes in stress due to CO_2 pressure may alter subsurface rock formations.	Induced seismicity, caprock fracture	Seismic monitoring, pressure control
Mineral Dissolution	CO_2 reacts with minerals, dissolving carbonates and silicates.	Increased porosity, potential for leakage pathways	Geochemical modeling, fluid sampling
Mineral Precipitation	CO_2 interaction forms stable carbonates that may clog pores.	Reduced permeability, injection efficiency	Core sampling, reactive transport simulations
Pore Pressure Changes	Elevated injection pressure modifies fluid dynamics and structural stability.	Reservoir fracturing, fault reactivation	Reservoir simulation, pressure sensors

IV. ENVIRONMENTAL AND CLIMATE IMPACTS

➢ *Long-Term CO_2 Sequestration Potential*

The long-term sequestration potential of CO_2 in geological formations, particularly within depleted oil reservoirs, represents a cornerstone in global carbon management strategies. These formations provide secure and voluminous storage capacity, often benefiting from extensive historical data and existing infrastructure. Once injected, CO_2 can be retained through multiple trapping mechanisms structural, residual, solubility, and mineral trapping which evolve over time to enhance permanence. Structural trapping, facilitated by caprock integrity, serves as the primary containment in the short term, while mineralization through geochemical reactions gradually converts CO_2 into stable carbonate compounds, ensuring long-term immobilization (Kelemen et al., 2023).

Successful demonstration projects such as Sleipner in Norway and the Weyburn project in Canada have provided empirical evidence supporting the viability of CO_2 storage over decadal timeframes. These initiatives highlight that with rigorous site selection, monitoring, and pressure management, reservoirs can retain injected CO_2 with minimal risk of leakage. Reservoir modeling, seismic surveys, and tracer technologies have further improved the predictability of storage performance (Ringrose et al., 2021). As part of CO_2-EOR schemes, the dual benefit of hydrocarbon recovery and long-term carbon sequestration positions oil fields as both energy assets and climate mitigation tools in a circular carbon economy.

➢ *Reduction in Carbon Footprint of Oil Production*

The integration of carbon dioxide (CO_2) capture with enhanced oil recovery (EOR) presents a transformative opportunity to reduce the carbon footprint of hydrocarbon production significantly. By injecting captured atmospheric CO_2 into oil reservoirs, not only is additional oil mobilized, but a substantial portion of the CO_2 remains sequestered underground, thereby preventing its release into the atmosphere. According to Zhang et al. (2023) as presented in figure 3, lifecycle assessments reveal that oil produced through CO_2-EOR can achieve net carbon reductions of up to 60% when compared to conventional extraction methods. This is particularly effective when the injected CO_2 is derived from point sources such as power plants or industrial facilities, contributing to broader emission mitigation strategies.

Moreover, CO_2-EOR enables the oil sector to transition toward climate-resilient practices without compromising productivity. Muggeridge et al. (2022) emphasize that implementing CCS-EOR systems across oil fields globally could offset as much as 140 million tonnes of CO_2 annually. Additionally, incorporating monitoring technologies ensures accurate measurement, reporting, and verification (MRV) of emissions savings, reinforcing transparency and regulatory compliance (Azonuche &Enyejo, 2024). As energy policies tighten and carbon pricing mechanisms become more prevalent, this integration emerges as a viable pathway for decarbonizing fossil fuel operations while extending the economic lifespan of mature reservoirs.

Figure 3 illustrate the image plays a critical role in reducing the carbon footprint of oil production by capturing carbon dioxide emissions from high-emitting sources such as power plants, steel, and cement industries. In the context of oil production, this technology can be integrated to capture CO_2 released during extraction, refining, and processing stages. Once captured, the CO_2 is transported via pipelines or ships to designated sites where it is either stored deep underground (such as in depleted oil reservoirs or saline aquifers) or utilized for other industrial purposes like enhanced oil recovery (EOR) or chemical production. By preventing CO_2 from being released into the atmosphere and instead repurposing or securely storing it, the CCUS process significantly mitigates greenhouse gas emissions, supporting more sustainable and environmentally responsible oil production.

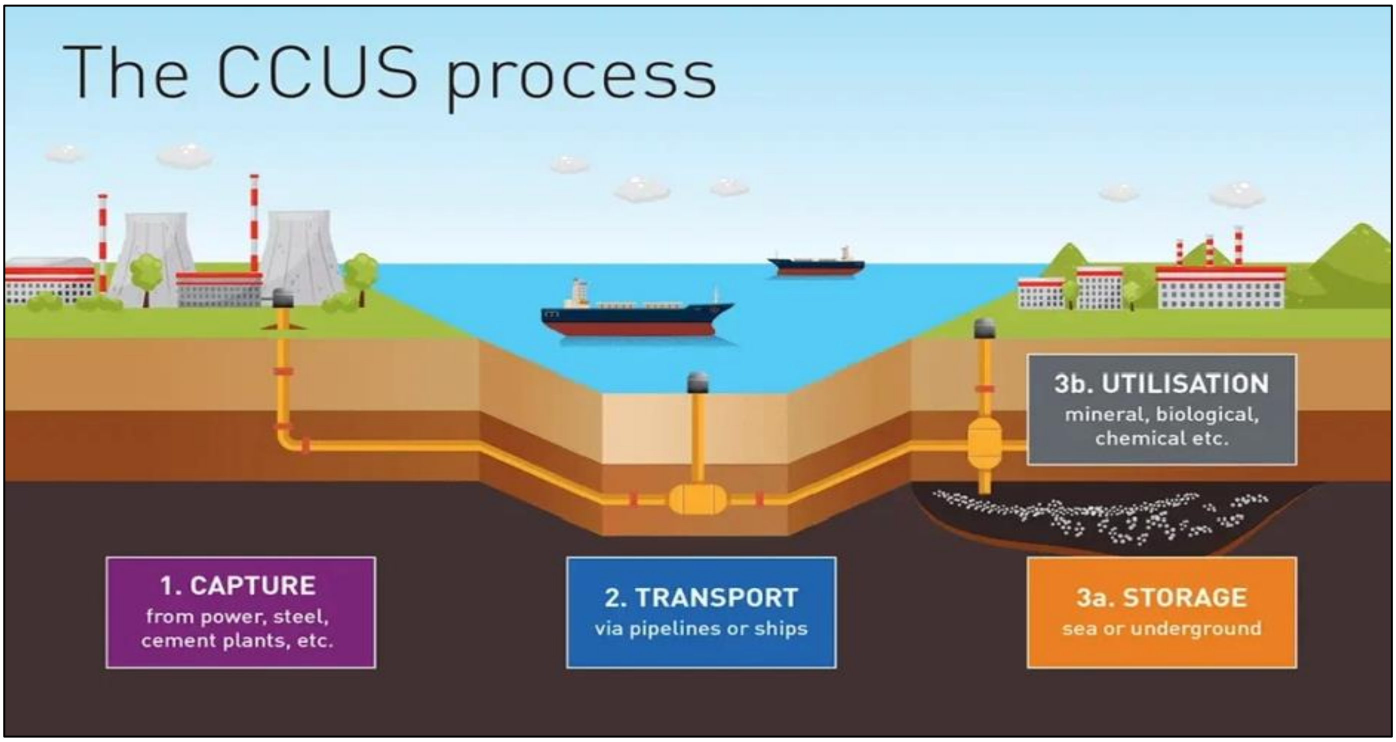

Fig 3 Picture of CCUS Integration for Low-Carbon Oil Production (Zhang et al. 2023).

➢ *Risk Assessment and Leakage Mitigation*

Robust risk assessment and proactive leakage mitigation are critical to ensuring the environmental integrity of carbon capture and storage (CCS) projects. The primary risks associated with CO_2 storage include caprock failure, fault reactivation, and wellbore leakage, which can compromise containment. Alcalde et al. (2023) as represented in table 3, underscore the importance of integrating geomechanical modeling with geochemical surveillance to predict and preempt leakage pathways. Their study highlights that continuous monitoring of pressure buildup and geochemical tracers enhances early detection capabilities, thereby reducing uncertainty in risk predictions and improving containment security.

In addition to modeling, operational safeguards such as pressure management and brine extraction have proven effective in mitigating leakage risk, particularly in deep saline aquifers. Cihan et al. (2022) demonstrate that pressure-driven migration of CO_2 can be counteracted by deploying engineered mitigation tactics, including pressure relief wells and adaptive injection schemes. Their findings suggest that incorporating real-time simulation feedback into storage operations can reduce the likelihood of unintended plume migration and ensure long-term storage integrity. These practices, when embedded into site-specific regulatory frameworks, are essential to the scalability and societal acceptance of large-scale CCS deployment.

Table 3 Summary of Risk Assessment and Leakage Mitigation

Risk Source	Description	Potential Consequences	Mitigation/Monitoring Strategies
Wellbore Integrity Failure	CO_2 escapes through abandoned or poorly sealed wells.	Groundwater contamination, atmospheric release	Regular well integrity testing, proper sealing practices
Fault and Fracture Pathways	Natural or induced fractures provide escape routes for CO_2.	Induced seismicity, surface leakage	3D seismic surveys, geomechanical modeling
Caprock Breach	Overpressure or chemical reactions weaken the seal integrity.	Loss of storage containment	Pressure control, reactive transport monitoring
Infrastructure Failure	Surface equipment failure or pipeline leaks during transport.	Health hazards, CO_2 loss	Routine maintenance, automated leak detection systems

V. ECONOMIC AND INFRASTRUCTURAL CONSIDERATIONS

➢ *Cost–Benefit Analysis of CO_2-EOR Projects*

The cost–benefit analysis of CO_2-enhanced oil recovery (CO_2-EOR) projects reveals a complex interplay between financial viability and environmental benefits. According to Godec et al. (2022) as represented in table 4, while the capital investment for CO_2 capture, transport, and injection infrastructure is substantial, the revenues generated from increased oil production can offset these costs, particularly in mature reservoirs. Their analysis indicates that CO_2-EOR can serve as a transitional carbon management strategy, especially when aligned with carbon credits and tax incentives that improve economic performance (Okeke, et al., 2024). However, profitability hinges on optimized reservoir conditions, efficient CO_2 utilization rates, and minimal leakage risks.

Wang et al. (2023) further emphasize that the financial attractiveness of CO_2-EOR is highly sensitive to fluctuations in oil prices and carbon pricing policies. Through integrated modeling, they demonstrate that under high carbon price scenarios, CO_2-EOR not only becomes economically viable but also yields net-negative emissions, reinforcing its dual value in hydrocarbon recovery and emissions reduction. For example, in scenarios with carbon prices above $60 per ton, the net present value (NPV) of CO_2-EOR projects significantly improves, making them competitive with other mitigation pathways. This underscores the necessity of policy alignment and technological efficiency in maximizing the socio-economic benefits of CO_2-EOR deployment.

Table 4 Summary of Cost–Benefit Analysis of CO_2-EOR Projects

Cost/Benefit Component	Description	Economic Impact	Strategic Considerations
CO_2 Capture and Compression	Cost of capturing CO_2 from industrial sources and compressing it for transport.	High initial capital and operational expenditures	May be offset by tax credits or carbon pricing incentives
Transportation Infrastructure	Building pipelines or utilizing existing networks to deliver CO_2 to reservoirs.	Moderate to high costs depending on distance and terrain	Regional planning can reduce infrastructure costs
Incremental Oil Recovery	Additional oil recovered through CO_2 injection into reservoirs.	Increases project revenues and extends field life	Market prices of oil influence overall profitability
Environmental and Regulatory Benefits	Avoided emissions penalties and potential carbon credits.	Long-term financial savings and improved ESG ratings	Enhances public acceptance and investment attractiveness

➢ *Use of Existing Oil and Gas Infrastructure*

Utilizing existing oil and gas infrastructure presents a cost-effective and technically viable pathway to accelerate atmospheric CO_2 capture integration with enhanced oil recovery (EOR) (Azonuche &Enyejo, 2024).

Infrastructure such as pipelines, compressors, injection wells, and monitoring systems can be repurposed to support CO_2 transport and storage, significantly reducing capital expenditure and deployment timeframes as presented in figure 4 (Li et al., 2023). This strategic reuse not only minimizes environmental disturbance compared to greenfield development but also offers logistical advantages by capitalizing on already mapped and regulated subsurface formations.

From a techno-economic standpoint, retrofitting legacy systems for CO_2-EOR is particularly attractive in mature oil fields, where the decline in hydrocarbon production aligns with the need for carbon storage solutions. However, challenges such as corrosion management, pressure containment, and ensuring regulatory compliance must be addressed during the adaptation process (Tang et al., 2022). For instance, older pipelines may require internal coating or lining to handle the acidic properties of CO_2-rich fluids. Nonetheless, the integration of CO_2 capture technologies with existing oilfield assets represents a pragmatic step toward sustainable domestic hydrocarbon production while contributing to national emissions reduction goals (Azonuche &Enyejo, 2024).

Figure 4 depicts workers inspecting industrial equipment, likely part of an oil and gas facility, highlighting the use of existing infrastructure in the sector. Leveraging current pipelines, storage tanks, and processing units can optimize production and reduce costs, as these assets are already integrated into operational networks.

Maintenance and upgrades, as shown by the workers' activities, ensure safety and efficiency, extending the lifespan of the infrastructure. This approach supports sustainable energy strategies by repurposing established systems for new technologies, such as carbon capture or hydrogen production, while meeting ongoing global energy demands.

Fig 4 Picture of Oil and Gas Infrastructure Inspection (Alobaidi et al., 2022).

- *Incentives and Carbon Credit Markets*

The evolution of carbon credit markets and the development of robust incentive structures have become crucial drivers in scaling up CO_2-EOR projects. Governments and international climate frameworks now recognize CO_2-EOR as a dual-purpose technology enhancing oil recovery while storing anthropogenic CO_2. This has led to the monetization of avoided emissions through carbon credit schemes, which allow operators to sell carbon offsets in regulated and voluntary markets (Wang et al., 2023). Such financial instruments not only improve the return on investment but also lower the perceived risk for private sector involvement in CO_2 capture and storage projects. For instance, credits issued under the Clean Development Mechanism (CDM) or emerging Article 6 frameworks under the Paris Agreement have provided precedents for transboundary carbon trading (Ononiwu et al., 2023).

In addition to market-based instruments, fiscal incentives such as tax credits, low-interest loans, and grants have proven instrumental in mobilizing capital toward CO_2-EOR projects. In jurisdictions like the United States, the Section 45Q tax credit offers up to $85 per ton for geologically stored CO_2, incentivizing both oil companies and industrial emitters (Alobaidi et al., 2022). These mechanisms foster innovation, drive infrastructure investment, and support the transition toward low-carbon energy systems, aligning seamlessly with the integrated policy and economic findings of this study.

VI. ENERGY SECURITY AND POLICY IMPLICATIONS

- *Enhancing Domestic Oil Production and Energy Independence*

The integration of CO_2-enhanced oil recovery (CO_2-EOR) into national energy strategies has emerged as a pivotal tool for enhancing domestic oil production while concurrently reducing dependence on imported crude. By injecting captured CO_2 into mature reservoirs, oil recovery rates can be improved by up to 20%, thereby extending the productive life of aging fields without the need for new explorations as presented in figure 5 (Aziz et al., 2023). This technology not only revitalizes declining reservoirs but also offers a cleaner alternative to conventional oil extraction, thus aligning with both energy and environmental policy goals. Countries with large volumes of anthropogenic CO_2, such as Nigeria or India, stand to gain significantly by linking industrial emissions to nearby oil fields through CO_2-EOR infrastructure.

From a policy standpoint, leveraging CO_2-EOR for domestic energy security reduces the geopolitical risks associated with volatile oil markets. It enables governments to buffer supply shocks while stabilizing prices through increased self-sufficiency (Rahman et al., 2022). Furthermore, by coupling EOR with carbon capture, national strategies can simultaneously address economic development and climate commitments under the Paris Agreement. This dual benefit directly supports the findings of this study regarding the economic and strategic viability of EOR-driven oil production.

Figure 5 shows an oil pump jack in operation, a key component in enhancing domestic oil production and fostering energy independence. By utilizing such equipment, countries can increase their crude oil extraction from local reserves, reducing reliance on foreign imports. Efficient operation and maintenance of pump jacks, as depicted, support a steady domestic supply, stabilizing energy prices and bolstering economic resilience. Investments in expanding and modernizing these systems can further boost output, aligning with policies aimed at securing long-term energy self-sufficiency while minimizing geopolitical vulnerabilities.

Fig 5 Picture of Active Oil Extraction Unit at Work (Aziz et al., 2023).

➢ *National and International Climate Policy Alignment*

The alignment of national and international climate policies is central to sustainable development and energy sector transition, especially for resource-rich countries navigating post-carbon futures. As nations increase domestic energy production through carbon-intensive methods like enhanced oil recovery (EOR), there is a compelling need to ensure that these initiatives do not conflict with global emission reduction targets. Rogelj et al. (2023) as represented in table 5 emphasize that national mitigation strategies must integrate systemic emissions monitoring and sector-specific carbon budgets to remain consistent with the Paris Agreement's 1.5°C trajectory. For example, countries like Norway and the UK have embedded decarbonization milestones into their domestic energy policies while simultaneously advancing energy security.

Moreover, effective climate diplomacy hinges on transparent implementation of domestic policies that complement multilateral agreements. Jakob and Steckel (2022) argue that well-designed national frameworks generate positive spillovers by encouraging other countries to adopt similar climate governance architectures. This harmonization is particularly vital for developing economies seeking to attract climate finance and technology transfer (Atalor et al., 2023). Therefore, this study's findings underscore the importance of synchronizing EOR and carbon capture strategies with both national decarbonization plans and international climate obligations (Ononiwu et al., 2023).

Table 5 Summary of National and International Climate Policy Alignment

Policy Dimension	**Description**	**Implications for CO_2-EOR Projects**	**Strategic Alignment Opportunities**
National Climate Commitments	Policies such as Nationally Determined Contributions (NDCs) under the Paris Agreement.	Encourages domestic carbon reduction strategies and supports CCUS adoption.	Aligning CO_2-EOR with national goals can attract public funding.
International Emission Standards	Global frameworks like the IPCC guidelines and carbon market mechanisms.	Requires adherence to reporting and monitoring standards for credibility.	Participation in global carbon markets and credit systems.
Cross-Border Regulatory Harmonization	Agreements to standardize CO_2 transport and storage across nations.	Facilitates multinational CO_2-EOR projects and reduces legal uncertainties.	Enables shared infrastructure and regional climate cooperation.

➤ *Public Perception and Regulatory Frameworks*

James et al., (2023), understanding public perception and regulatory frameworks is pivotal to the successful implementation of carbon dioxide-enhanced oil recovery (CO_2-EOR) technologies. Public acceptance hinges largely on transparent governance, the credibility of regulatory institutions, and the perceived environmental benefits. According to Thomas and Parsons (2022), trust in both government and industry actors significantly influences public attitudes toward carbon capture and storage (CCS), particularly when associated with fossil fuel production. In regions with histories of regulatory failure or environmental degradation, skepticism toward CO_2-EOR projects can become a major barrier, regardless of their technical merit or climate potential. Consequently, effective stakeholder engagement and community inclusion in policy dialogues are essential to counteract misinformation and build legitimacy.

On the regulatory side, policy frameworks must balance innovation with rigorous oversight to ensure safety, accountability, and emissions integrity. Wolske and Stern (2023) emphasize that robust regulatory design characterized by transparency, consistent enforcement, and adaptive legal mechanisms enhances public confidence and fosters broader societal support for climate interventions. Aligning these frameworks with environmental justice principles is also critical, especially in communities disproportionately affected by oil and gas operations (James et al., 2024). Thus, this study's findings stress the integration of social license considerations with regulatory robustness to advance CO_2-EOR adoption.

VII. CONCLUSION

➤ *Synthesis of Key Insights*

This study has demonstrated that integrating atmospheric CO_2 capture with enhanced oil recovery (EOR) in mature reservoirs offers a powerful dual solution to address climate change while sustaining domestic hydrocarbon production. The approach leverages existing infrastructure and reservoir knowledge, transforming traditional oil extraction into a carbon mitigation process. Technological advancements in direct air capture, reservoir injection techniques, and monitoring systems have significantly improved the efficiency, safety, and scalability of this integration. The findings underscore that the environmental benefits, particularly in reducing lifecycle carbon intensity, can be substantial when CO_2-EOR is implemented with rigorous operational standards and supported by renewable energy inputs. Economically, the strategy aligns with market mechanisms such as carbon credits and incentives, improving financial viability in varying policy and price scenarios. Moreover, the approach enhances energy security by extending the productive lifespan of domestic oil fields, reducing import dependence, and stabilizing national energy supply. Collectively, the evidence supports the view that CO_2-EOR can act as a transitional technology, bridging the current fossil fuel-dependent system with future low-carbon energy models. By integrating technical innovation, sound policy frameworks, and public engagement, the method holds significant promise as a cornerstone of sustainable hydrocarbon production and climate-aligned energy strategy in the 21st century.

➤ *Strategic and Policy Implications*

The integration of CO_2 capture and EOR has clear implications for national energy strategies and climate policy alignment. Strategically, it provides an avenue for oil-producing nations to reconcile economic reliance on fossil fuels with commitments to emission reductions. By embedding CO_2-EOR within national decarbonization plans, governments can capitalize on its capacity to generate both environmental and economic value. This alignment also facilitates participation in international carbon markets and fosters eligibility for climate finance and technology transfer programs. Policymakers can further amplify benefits by creating stable regulatory environments that encourage investment, ensure environmental integrity, and maintain public trust. Incentives such as tax credits, grants, and carbon pricing frameworks can accelerate project deployment and stimulate technological innovation. On a global scale, harmonizing cross-border standards for CO_2 transport and storage would enable multinational projects and shared infrastructure, reducing costs and broadening adoption. Additionally, integrating CO_2-EOR with renewable energy sources and hydrogen production could position participating countries as leaders in hybrid low-carbon energy systems. The policy challenge lies in balancing short-term economic gains from enhanced oil production with long-term climate objectives, ensuring that the overall carbon balance remains favorable. The study's findings emphasize that policy coherence, transparency, and stakeholder inclusion are vital for scaling the technology while upholding environmental and social accountability.

➤ *Pathways for Future Development*

The future of atmospheric CO_2 capture and EOR integration depends on sustained technological innovation, collaborative infrastructure development, and adaptive deployment models. Scaling this approach globally requires tailoring solutions to diverse geological, economic, and regulatory contexts. Advanced materials for CO_2 capture, predictive analytics for reservoir performance, and digital twin simulations will enhance operational efficiency while reducing costs and risks. Developing modular and mobile capture units can enable flexible deployment near optimal storage sites, improving feasibility in remote or infrastructure-limited regions. Public–private partnerships will be essential for financing large-scale projects, supported by international agreements that standardize monitoring, verification, and reporting protocols. In emerging economies, targeted capacity-building programs and knowledge-sharing platforms can bridge technical and institutional gaps, enabling broader participation. Furthermore, integrating CO_2-EOR with other decarbonization strategies, such as bioenergy with carbon capture and storage (BECCS) or green hydrogen production, can multiply climate benefits and diversify revenue streams. As carbon pricing mechanisms mature, the economic case for CO_2-EOR will strengthen, incentivizing adoption across both developed and developing markets. Ultimately, the path forward involves treating CO_2 not merely as a waste product but as a valuable resource within a circular carbon economy. This transformation can reinforce energy resilience, stimulate innovation, and deliver measurable progress toward global net-zero targets.

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