Views & Comments

Challenges in the Large-Scale Deployment of CCUS

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1. Introduction

Climate change mitigation pathways aimed at limiting global anthropogenic carbon dioxide (CO_2) emissions while striving to constrain the global temperature increase to below 2 °C—as outlined by the Intergovernmental Panel on Climate Change (IPCC)—consistently predict the widespread implementation of CO_2 geological storage on a global scale. Achieving net-zero emissions requires a significant boost in carbon storage from 40 to 5000 million tonnes (MT) annually by 2050 [1]. Currently, the global carbon capture, utilization, and storage (CCUS) landscape comprises around 45 commercial-scale projects, with 700 projects underway across various development stages. The Yanchang CCUS project in China is a notable example of successfully combining coal chemical plants with CO_2 resource-utilization technology. This innovative approach yields multiple benefits, including clean coal utilization, enhanced energy production, and significant carbon emission reduction [2,3]. By 2030, CCUS could capture 435 MT of CO_2 annually and store 615 MT [4]. However, the pace of commercial-scale CCUS project deployments is still far less than the projected targets for achieving net-zero emissions. This is because the CCUS sector has encountered substantial challenges in achieving full-scale commercial deployment. This article discusses key roadblocks in CCUS deployment including technical, operational, and regulatory aspects of such projects. It also explores the complexities and difficulties associated with deploying CCUS technologies, emphasizing the critical need for targeted strategies to mitigate these challenges and accelerate deployment Fig. 1.

2. Geological challenges

Geological carbon sequestration requires thorough site characterization to ensure high injection rates, substantial storage capacity, and long-term CO_2 storage and containment potential. Furthermore, precise subsurface modeling relies on characterization of the multi-physics and multiscale nature of the sequestration process, which necessitates the employment of robust dynamic simulators and numerical tools incorporating pressure, temperature, and geochemical interactions to predict migration, trapping, and storage capacity. Effective site characterization can also be impacted by inconsistent data quality and coverage, which are primarily due to differences in data-collection methods, resolution, data formats, and interpretative methodologies. Site-specific data are frequently inadequate and sparse, typically being restricted to shallow depths and limited spatial coverage [5]. This can lead to inaccurate containment assessments, underestimation or overestimation of storage capacity, inaccurate CO_2 migration/trapping predictions, and insufficient identification of potential leakage pathways [6].

Recently, research on site characterization has highlighted several key challenges, including delineating geological structures, understanding the dynamic interactions between injected CO_2 and the geological framework, quantifying storage capacity, and assessing the technical and economic viability of proposed sites. In this regard, three-dimensional (3D) geological and dynamic modeling and visualization technologies have become crucial in CO_2 geological storage. The technical evolution of 3D geological modeling is characterized by the seamless integration of multidimensional exploration and high-resolution imaging technologies. This integration drives advancements toward high-resolution mapping and modeling by enhancing transparency and accessibility and enabling machine learning and data-driven decision-making.

However, conventional 3D geological framework models often struggle to accurately capture the intricate complexities of geological formations, particularly when confronted with heterogeneous rock matrices and complex fracture networks. For example, the Wilcox Trend in the Gulf of Mexico presents significant challenges for 3D seismic resolution due to the extreme conditions, which include deep-water environments with extreme depths (up to 35 000 feet; 1 feet = 30.48 cm) and thick allochthonous salt formations that can span 10 000–20 000 feet [7]. The combination of these factors compromises the accuracy and reliability of 3D seismic imaging. Such models fail to capture the spatial variability in basic petrophysical properties such as porosity and permeability, which can exhibit distinct heterogeneity even at localized scales. Furthermore, fractures occurring across diverse scales can
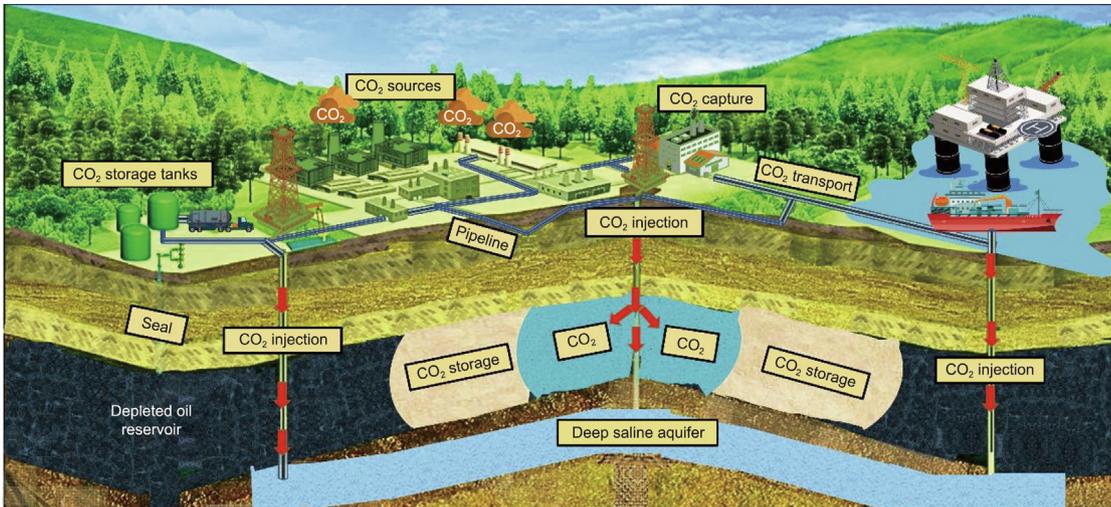
Fig. 1. Schematics of an integrated CCUS system.

significantly influence fluid flow dynamics and containment, posing an additional layer of complexity that existing models may not adequately address.

In this regard, machine learning algorithms can assist in optimizing 3D modeling workflows. However, their potential is hindered by data scarcity, highlighting the need for the innovative integration of technologies across multiple disciplines in order to integrate 3D geological and structural models and ensure robust evaluations at multiple time and spatial scales. Although multiscale 3D geological models have been successfully developed across the macro to micro scales, the lack of robust cross-scale integration and integrated methodologies slows down the development of cohesive and high-fidelity models, ultimately limiting informed decision-making for CO_2 storage applications. Therefore, the cross-disciplinary aspect of CCUS is important for the formation of integrated teams that can evaluate, integrate, execute, and monitor such projects.

3. Transportation challenges

The development of CO_2 transportation infrastructure is essential for large-scale CCUS operations. For example, extensive pipeline networks and potentially cross-border transport systems are necessary to transfer CO_2 from capture sites (e.g., power plants and industrial facilities) to subsequent storage locations. According to a recent study, CO_2 transport and storage capacities have surged, with 260 MT CO_2 per year of new capacity since February 2023. The projected capacity for 2030 is 615 MT CO_2 per year, which is still short of the 1000 MT CO_2 per year required to achieve net-zero emissions [8]. Therefore, there is an urgent need to develop robust CO_2 transportation networks and infrastructure and to expand storage capacity.

The primary obstacle to effective carbon storage and transportation is the lack of integrated carbon management infrastructure connecting emission sources to storage sites (i.e., source and sink matching). In this regard, an efficient pipeline network is a key component in addressing CO_2 transportation challenges, as it provides a safe, efficient, and cost-effective connection between emission sources and storage facilities [3]. However, CO_2 pipeline transportation presents various challenges such as pipeline design and integrity issues; flow assurance and operational problems;

short- and long-term health, safety, and environmental (HSE) aspects of projects; and required pipeline permits. In addition, the presence of impurities in CO_2 streams generates further complications, especially in pipeline networks and gathering centers where multiple CO_2 sources converge. For example, corrosion-inducing impurities such as hydrogen sulfide (H_2S) and sulfur oxides (SO_x) can significantly increase material costs. On the other hand, non-condensable gases such as oxygen (O_2), nitrogen (N_2), and argon (Ar) elevate the operating pressures within pipelines and within the reservoir, as they can accumulate over time. This increase in pressure, which is commonly observed in pipelines across the United States and Canada, leads to higher transportation costs. Furthermore, free water within CO_2 (and other acid gases) [9] pose significant problems, particularly regarding hydrate formations and accelerated corrosion rates on pipeline inner walls [8]. The specifications for free water content in CO_2 vary across guidelines, ranging from 40 to 500 parts per million (ppm). However, the maximum permissible water content in CO_2 streams is uncertain, emphasizing the need for standardized guidelines.

In addition, efficient CO_2 transportation requires the CO_2 to be in its supercritical (dense) phase. However, this phase is notoriously sensitive to elevation changes and impurities, which can significantly impact CO_2 phase behavior and process thermodynamics. Such sensitivity can affect the depressurization distance, flow regimes, and pipeline operating/transportation conditions. Therefore, to mitigate these challenges, it is necessary to optimize pipeline sizing, elevation, depressurization distance, pump/compressor station placement, and energy requirements with due diligence.

CO_2 pipeline design and operation require a comprehensive techno-economic framework to mitigate risks and uncertainties [10]. This framework should integrate economic evaluations of various aspects of the pipeline while addressing technical challenges such as pipeline design, operations, and financing. Similarly, commercial risks in CO_2 pipelines include project delays, abandonment, and cancellation, mainly due to high capital and operational costs. Operational costs significantly impact project feasibility, especially over long distances or challenging terrains, as does the continuous remediation of various flow-assurance and/or corrosion-related problems. Pipeline transport has the lowest emissions and costs but it requires a higher upfront investment. Therefore, reliable techno-economic models are essential for the successful commercial deployment of CCUS pipelines.

4. CCUS safety and monitoring challenges

Safe operation of CCUS prioritizes the protection of humans, the environment, and the infrastructure from potential CO_2-related hazards. This comprehensive approach includes secure containment, leak detection and remediation, corrosion mitigation, pressure regulation, and planning for emergency response. Advanced CO_2 monitoring combines real-time injection monitoring, tracking the propagation and movement of CO_2 in the subsurface, and innovative leak-detection technologies for surface and subsurface conditions [11,12]. The primary objective of this monitoring is to track CO_2 plume migration and verify containment within the target formation, while addressing challenges in detecting potential leakage beyond the intended subsurface geological boundaries.

CO_2 monitoring is affected by several challenges that increase its complexity; these include predicting complex chemical reactions, understanding fault/fracture dynamics in response to CO_2 injection, and designing optimal seismic surveys for accurate CO_2 plume detection. Various remote CO_2 monitoring techniques have been proposed, including four-dimensional (4D) seismic monitoring, 4D controlled-source electromagnetic measurements, microseismic monitoring, interferometric synthetic aperture radar (InSAR), and tilt meter/Global Positioning System (GPS) monitoring. Similarly, advanced geophysical monitoring techniques, such as the combination of 4D seismic and electromagnetic surveys, may enable precise plume tracking and estimation of free gas saturation [13]. However, the limitations of such techniques include low resolution and depth uncertainties. For example, for high-resolution readings the optimal depth range is generally restricted to 3 km or less [13], hampering the effective characterization of faults and fractures. The accuracy of 4D seismic surveys is also hindered by challenges in data acquisition repeatability, processing consistency, and the precision of interpretative methodologies. Practical processing considerations include enhancing repeatability, preserving amplitude information, and reducing turnaround time. Even borehole seismic surveys, which utilize high-resolution tomography and distributed acoustic sensing, present technical limitations (e.g., in identifying structural and stratigraphic traps, reduced bandwidth, and diminishing resolution).

Finally, the effective monitoring of CCUS systems relies heavily on high-performance computation to automate and parallelize complex tasks such as real-time data analysis, simulation, machine learning, and predictive analytics. However, despite significant advancements in the efficiency of computing power, issues persist, preventing the widespread adoption of CCUS monitoring technologies. Overcoming these challenges will enable monitoring systems to mitigate storage risks and ensure the safe deployment of CCUS technologies.

CCUS operations involve injecting CO_2 into underground reservoirs, which can induce geomechanical hazards such as pore pressure enhancement, stress redistribution, reservoir deformation, and loss of well integrity. Excessive CO_2 injection rates can pose significant risks, including downhole pressures that exceed the fracture pressure and induce tensile fractures. Well-stimulation techniques such as hydraulic fracturing and acidizing can mitigate this issue by improving the near-wellbore permeability. However, reservoir pore pressure alteration can trigger an unavoidable poroelastic response, potentially extending to the reservoir surface. This can lead to shear failure at the caprock–reservoir interface, compromising the caprock's stability and potentially destabilizing its sealing capacity. Additionally, excessive CO_2 injection can compromise well integrity and contaminate water resources due to damaged cement, casing gaps, and CO_2-induced corrosion [14].

Consequently, CO_2 injection can increase the compaction strain in reservoirs and thereby affect the stress evolution within the reservoir, transferring stress to the surrounding subsurface formations and potentially causing irreversible subsidence. In this regard, further research is needed to study the impact of CO_2 injection on geological subsurface chemical-mediated compaction.

Furthermore, excessive CO_2 injection leading to excessive local high pressures can reactivate faults by altering stress conditions, specifically decreasing the effective normal stress and potentially triggering shear failure [15]. Fault reactivation prediction is difficult due to localized stress variations and heterogeneous fault properties. Local stress fields can deviate substantially from the regional crustal stress, and the fault structure and shear strength can exhibit significant variability. Research suggests that excessive fluid injection can trigger catastrophic seismic events. This was witnessed in Oklahoma during 2011–2012, when disposal well injections sparked a 5.6-magnitude earthquake that led to significant damage, including 14 destroyed buildings and two injuries [16]. Similarly significant seismic events can also be triggered by reactivating small faults (often hundreds of meters long) that intersect the injection zone. However, it is impossible to detect these zones through efficient seismic surveys, making it extremely challenging to determine the exact injection pressure that will trigger reactivation [17].

CO_2 injection can also alter the subsurface stress distributions and contribute to induced seismicity. Accurate prediction of induced seismicity relies on a comprehensive understanding of the intricate fault networks and dynamic stress fields. Currently, existing CO_2 storage projects have not experienced significant seismic activity. However, future large-scale CCUS operations, which will require substantial CO_2 injection volumes, pose a potential risk of induced seismicity. This risk is particularly concerning because predicting injection-induced seismicity remains a significant challenge largely due to uncertainties in stress fields, potentially hidden faults, and geomechanical properties. Therefore, for large-scale CCUS applications, characterizing complex fault systems with non-intuitive activation behavior becomes extremely important. Identifying the specific triggers that induce seismicity is one of the major challenges faced by the industry. In this regard, an understanding of the complex interplay between CO_2 injection, reservoir pressure, and the behavior of fault systems is crucial in minimizing the risk of induced seismicity.

Numerous methods have been developed for efficient induced seismic estimations in CO_2 storage projects, with the aim of mitigating the associated risks. Prominent theories include critical pressure theory (CPT), Biot theory, and fracture potential (FP) theory. However, in practical applications, each theory has its limitations. For example, CPT neglects large-scale tectonic faults, Biot theory overlooks stress-corrosion-induced failure, and FP models struggle to provide reliable onsite seismic activity predictions. In contrast, the Dieterich model integrates stress changes, tectonic activity, and reservoir dynamics but encounters challenges in parameter calibration, sensitivity, and applicability to complex faults. Similarly, predicting injection-induced seismicity involves statistical, physics-based, and hybrid methods. Statistical models use seismic correlations, while physics-based models utilize geological and geophysical data. However, both approaches have limitations, and large-magnitude events remain unpredictable. Other predictive methods include empirical and simulation approaches. Empirical methods simplify physical processes but rely on observed seismic data, which results in comprised accuracy due to model fidelity and data limitations. Numerical simulations applied in carbon geological storage, enhanced

geothermal system, and wastewater injection better capture complex scenarios but have difficulty obtaining accurate characterization data for model calibration. Nevertheless, ensuring caprock stability and monitoring pore pressure buildup are crucial to prevent induced seismicity and mitigate the environmental risks associated with CO_2 injection.

5. Policy and regulatory challenges

A robust regulatory framework and supportive governmental policies are vital for scaling up CCUS operations. Effective policies should include carbon pricing mechanisms, targeted subsidies, streamlined approval processes, and cross-border agreements to create a favorable environment for CCUS development. However, several challenges hinder progress, including inconsistent regulatory frameworks, lengthy permitting processes, and a lack of standardized storage and transport regulations, creating uncertainty and delaying project implementation. Moreover, insufficient policy stability discourages long-term investment, underscoring the need for stable and long-term policy commitments. Thus, the establishment of a robust regulatory framework is paramount for facilitating large-scale CCUS investment and ensuring long-term project viability. A transparent and efficient regulatory framework requires streamlined permitting processes, clearly defined licensing criteria, strict regulations on storage sites, and active public engagement, in order to establish a stable and attractive environment for the industry.

Operating large-scale CCUS projects in remote or infrastructure-poor regions presents additional challenges. Therefore, securing early-stage financing is particularly important in regions with high capital costs. Moreover, implementing well-designed market mechanisms such as carbon pricing and targeted tax incentives can significantly improve the efficiency and scalability of CCUS deployment. The widespread adoption of carbon pricing is hindered because many existing schemes lack the necessary price threshold to make CCUS economically viable.

6. Conclusions and recommendations

This study highlighted key findings and challenges in deploying large-scale CCUS projects, emphasizing the need to address site characterization, CO_2 transport and storage, relevant data requirements, efficient monitoring, and regulatory/economic elements in order to ensure reliable and scalable operations. To promote the efficient deployment of large-scale CCUS projects, the following recommendations are made:

(1) CO_2 monitoring is crucial for large-scale CCUS projects. It combines real-time tracking, subsurface surveillance, and leak detection to verify containment and detect potential breaches. To mitigate these challenges, the latest seismic monitoring techniques, such as time-lapse 4D seismic monitoring, passive seismic monitoring, or ground-penetrating radars (GPR) should be employed.

(2) Effective geological carbon sequestration requires comprehensive site characterization and dynamic subsurface simulations with the right and scalable input data. However, a lack of data and inconsistent data quality and formats complicate this process. A multi-faceted approach is needed to address these challenges, including standardizing data-collection methods and establishing centralized repositories that are easily accessible to the public.

(3) Models/simulators should have the correct processes implemented for physical conditions. Due to the multi-scale (in the spatial and time dimensions) nature of the problem, faster models are needed for multiple scenario and uncertainty analyses, as well as in the context of the integration of real-time data.

(4) CO_2 pipeline transportation is an important factor in the efficient deployment of large-scale CCUS operations; however, it presents complex challenges due to the corrosive nature of the material being transported, requiring specialized design, materials, and operational protocols. Therefore, it is imperative to ensure pipeline integrity, flow assurance, and HSE standards.

(5) Collective efforts are necessary to address technical, regulatory, and economic challenges. Collaborative efforts from policymakers can overcome barriers to CCUS implementation, unlocking the potential of CCUS to mitigate climate change and drive sustainable development.

Acknowledgments

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