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Progress and Implications of Carbon Dioxide Geological Utilization and Storage in the Oil and Gas Industry

Shu Yuan[1,2]

[1]State Key Laboratory of Petroleum Resources and Prospecting, College of Geosciences, China University of Petroleum, Beijing, China
[2]China-Portugal Joint Research Institute of Climate and Energy, China University of Petroleum, Beijing, China
Email: shuyuan@student.cup.edu.cn

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Abstract

Amid the global push for carbon neutrality, the oil and gas industry is undergoing a rapid low-carbon transition. Carbon dioxide geological utilization and storage (CGUS), a subset of carbon capture, utilization, and storage (CCUS) technologies, has emerged as a pivotal strategy due to its substantial potential for enhancing resource recovery and reducing carbon emissions. This study systematically evaluates the strategic initiatives of international oil companies in CGUS, examines global policy frameworks and technological advancements, and assesses the development of supporting infrastructure. Tailored to China's national context, it identifies key challenges in CGUS implementation within the oil and gas sector and proposes actionable recommendations. Key findings include: (1) CGUS is a cornerstone of the industry's low-carbon transition, with international firms achieving early commercialization through technological leadership, while Chinese companies, leveraging CO_2-enhanced oil recovery (CO_2-EOR) pilots, are scaling up large demonstration projects. (2) Globally, robust CGUS support systems are emerging, encompassing tax incentives, dedicated funds, carbon trading mechanisms, advanced reservoir evaluation and monitoring technologies, and standardized frameworks that facilitate large-scale deployment. (3) In China, CGUS faces economic, technical, and institutional barriers. Recommendations include accelerating infrastructure development, fostering innovative business models, refining policy incentives, advancing geological evaluation and monitoring technologies, and strengthening regulatory and carbon market integration to drive high-quality industry growth.

Keywords

Oil and Gas Industry, Carbon Dioxide, CCUS, Geological Carbon Storage,

Carbon Neutrality

1. Introduction

Since the Industrial Revolution, extensive fossil fuel exploitation has profoundly altered the global carbon cycle. By 2024, atmospheric CO_2 concentrations are projected to reach 422.5 ppm, a 52% increase from pre-industrial levels (approximately 278 ppm in 1750), with global mean temperatures rising by about 1.1˚C [1] [2]. This accelerating climate imbalance threatens ecosystem stability and sustainable development, prompting nearly 200 nations to adopt the Paris Agreement, establishing a carbon neutrality-centered governance framework. In 2020, China committed to its "dual carbon" goals of peaking emissions by 2030 and achieving neutrality by 2060, marking its integration into the global decarbonization effort.

The carbon neutrality imperative is reshaping the energy sector, presenting both challenges and opportunities for the oil and gas industry. Challenges include market contraction due to the rise of renewables and escalating compliance costs driven by carbon pricing and ESG standards. Conversely, carbon capture, utilization, and storage (CCUS) technologies, which encompass a broad range of methods to capture, utilize, and store CO_2, and its subset, carbon dioxide geological utilization and storage (CGUS), which focuses specifically on geological storage and utilization often linked to enhanced oil recovery (EOR), offer significant potential for gigaton-scale emission reductions. The International Energy Agency (IEA) projects that CCUS will account for 15% of global emission reductions by 2070 [3]. Leveraging decades of CO_2-EOR expertise, the oil and gas industry is well-positioned to lead in reservoir evaluation, storage engineering, and monitoring. Despite a global theoretical storage capacity of 8 - 55 trillion tons, actual storage in 2020 represented only 0.1% of annual emissions, underscoring industrialization gaps [4]. International oil majors are driving competitiveness through technological innovation and novel business models, positioning CGUS as a strategic pillar for industry transformation [5].

This study examines CGUS development in the oil and gas sector across three dimensions: (1) analyzing project deployments by global and Chinese oil companies to identify industry trends; (2) evaluating advancements in reservoir selection, drilling optimization, and leakage monitoring, alongside the economic feasibility of saline aquifer storage and EOR integration; and (3) assessing the role of policy, regulatory, and standardization frameworks in shaping the CGUS ecosystem. Drawing on China's resource and institutional context, we propose a comprehensive development strategy encompassing technological innovation, cost-sharing mechanisms, and international collaboration to support a tailored CGUS industry framework.

2. Strategic Importance of CGUS in the Oil and Gas Industry

2.1. Necessity under Carbon Neutrality Goals

CGUS is critical to achieving deep decarbonization under global carbon neutrality targets. The Intergovernmental Panel on Climate Change (IPCC) estimates that excluding CCUS would increase the cost of limiting warming to 2˚C by 138% [6], while the IEA underscores CGUS's role in delivering 15% of global emission reductions by 2070 [3]. By injecting captured CO_2 into deep saline aquifers or depleted reservoirs, CGUS offers vast storage potential (8 - 55 trillion tons globally) and long-term stability. However, with 2020 storage accounting for just 0.1% of emissions, significant barriers to technology transfer and commercialization persist, necessitating urgent ecosystem restructuring [4].

2.2. A Transformative Lever for the Oil and Gas Industry

The oil and gas sector, responsible for 5.1 billion tons of carbon emissions in 2022 (13.8% of global energy-related emissions), faces intense pressure to decarbonize [7] [8]. CGUS serves as a dual-purpose solution: (1) Emission Reduction and Efficiency: CO_2-EOR integrates storage with enhanced oil recovery, producing low-carbon oil and creating a profitable closed loop [9]. (2) Business Diversification: Leveraging geological and engineering expertise, oil companies can offer carbon storage services to high-emission sectors like cement and steel, while exploring markets such as blue hydrogen and carbon removal credits [10]. This dual approach mitigates stranded asset risks and fosters new revenue streams, enabling a transition from traditional energy providers to comprehensive carbon management entities.

3. Current State of CGUS Development

3.1. Industry Deployment Trends

The global oil and gas industry is prioritizing CGUS, adopting a dual strategy of onshore EOR storage and offshore saline aquifer storage. Saline aquifers, representing 98% of global storage capacity, are a competitive focus, while depleted reservoirs, supported by established geological data, dominate early projects [4] [11]. The sector is characterized by rapid technological advancement and scaling efforts.

3.1.1. International Oil Companies: Technological Leadership and Ecosystem Development

Leading oil companies are establishing dominance through integrated value chains and innovative business models (Table 1). Chevron's Gorgon project in Australia, the largest operational saline aquifer storage facility, has stored over 7 million tons of CO_2, targeting 25 million tons annually by 2100. ExxonMobil, utilizing a 1500-mile CO_2 pipeline network, has formed a dedicated carbon management division to deliver end-to-end capture, transport, and storage services [12]. Shell's subscription-based storage model supports 12 projects in regions like the

North Sea, aiming for 25 million tons/year by 2035 [13]. TotalEnergies, through strategic acquisitions, and bp, with its CCUS-low-carbon energy model, are advancing cross-border and industrial decarbonization initiatives, targeting significant capacity by 2030-2035. These international oil companies have been leading the transition to low-carbon energy and the development of the CCUS industry. They have successfully commercialized CCUS in a variety of geological and regulatory contexts, offering valuable, transferable lessons for China. These include advanced monitoring technologies and scalable business models that can be adapted to China's complex geological basins and its rapidly expanding carbon market. Europe's transnational CCUS deployment (such as the North Sea project) emphasizes international cooperation and can inspire China's inter-provincial coordination, such as the CCUS clusters in East China and North China.

Table 1. Key CGUS projects of global oil and gas companies.

Company	Core Projects and Metrics
Chevron	1. Gorgon (Australia): 4 M tons/year, world's largest saline aquifer project. 2. Bayou Bend (USA): 140,000 acres. 3. Quest (Canada): 1 M tons/year, 20% stake.
ExxonMobil	1. Houston Hub (USA): 100 M tons/year by 2040. 2. Java Sea (Indonesia): 3 B tons potential. 3. Daya Bay (China): 10 M tons/year offshore hub.
bp	1. East Coast Cluster (UK): 27 M tons/year by 2030. 2. Tangguh (Indonesia): 15 M tons initial capacity. 3. Texas (USA): 15 M tons/year.
Shell	1. Aramis (Netherlands): 5 M tons/year by 2030. 2. Daya Bay (China): 10 M tons/year. 3. Longship (Norway): >100 M tons potential.
TotalEnergies	1. Northern Lights (Norway): 10 M tons/year by 2030. 2. Bayou Bend (USA): 140,000 acres. 3. Aramis (Netherlands): 5 M tons/year by 2030.
CNPC	1. Songliao Basin: 3 M tons/year, 7.23 M tons stored. 2. Junggar Hub: 10 M-ton cluster planned.
Sinopec	1. Qilu-Shengli: First million-ton full-chain project. 2. East China: 10 M-ton cluster feasibility study.
CNOOC	1. Enping 15-1: >1.5 M tons stored, offshore breakthrough. 2. Daya Bay: 10 M-ton offshore cluster planned.

3.1.2. Chinese Oil Companies: Demonstration and Cluster Development

Chinese firms are advancing full-chain CGUS deployment. CNPC's Songliao Basin project has injected 1.592 million tons of CO_2 by 2023, targeting 3 million tons/year by 2025. Sinopec's Qilu Petrochemical-Shengli Oilfield project, China's first million-ton-scale CCUS initiative, operates a 100-km CO_2 pipeline and is exploring a 10-million-ton cluster in East China. CNOOC's Enping 15-1 project has stored over 1.5 million tons, with plans for a 10-million-ton offshore cluster, marking progress in offshore storage industrialization.

3.2. Technological Advancements

CGUS involves multiple processes, including CO_2 capture, transportation, and geological utilization and storage. While CO_2 capture benefits from several established technologies, the cost of capturing low-concentration CO_2 remains prohibitively high, estimated at 300 - 900 CNY/ton for sources like coal-fired power plants and steel mills [14]. Transportation primarily occurs via pipelines, tankers, or ships, with costs ranging from 0.9 - 1.4 CNY/(ton·km) [15]. The geological utilization and storage phase includes critical steps such as reservoir selection, storage potential assessment, drilling optimization, and leakage monitoring, with ongoing advancements enhancing both safety and economic feasibility. Currently, the various technologies underpinning CGUS are at different stages of maturity (**Figure 1**). This article will introduce the technological progress related to geological utilization and storage.

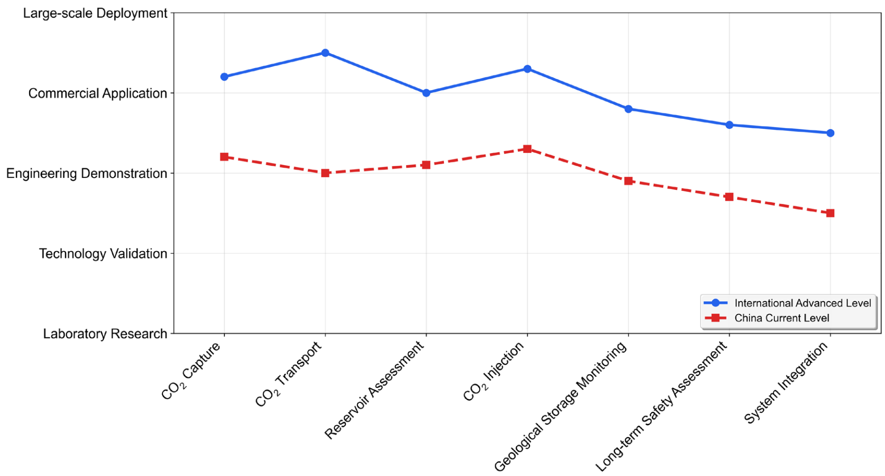

Figure 1. Maturity assessment of CO_2 geological utilization and storage technologies.

3.2.1. Reservoir Selection and Caprock Evaluation

Reservoir properties such as porosity and permeability are key to determining storage capacity. Caprock integrity, including its continuity and faulting, ensures long-term CO_2 containment. Regional planning focuses on caprock macro-characteristics, while engineering phases emphasize reservoir injectivity and caprock sealing capacity [16]. International standards, such as those in the USA and Australia, integrate capacity, injectivity, and economics into evaluation frameworks [17]-[19]. Due to China's complex basin structures and lower crustal stability, the China Geological Survey has developed a preliminary geological suitability grading system tailored to different reservoir types [20] [21].

3.2.2. Storage Potential Assessment

Accurate assessment is essential for effective storage planning. International frameworks involve four stages—national screening, basin evaluation, site characterization, and application—using geological and safety risk indicators. Methods like the CSLF "Pyramid Model" and US-DOE/USGS volumetric balance estimate storage capacity but often overlook dissolution trapping mechanisms [22]-[24]. In China, the RIPED & CUP method has been adapted to include CO_2 dissolution effects for continental reservoirs. However, challenges remain in determining staged recovery rates accurately, limiting its wider use [25] [26].

3.2.3. Drilling and Completion Optimization

Advancements in drilling and completion technologies enhance the safety, cost-effectiveness, and scalability of CO_2 storage. Optimized well designs—such as vertical, horizontal, and clustered multi-well configurations—improve reservoir coverage and injection efficiency [16] [27]. Gas-lift reverse circulation and air-foam drilling reduce time and costs in complex formations. Nanomaterial-enhanced cement slurries and dynamic sealing improve wellbore integrity and microfracture sealing. Corrosion protection is strengthened through anti-corrosion casings, advanced coatings, inhibitors, and smart safety systems for real-time risk monitoring [28]. These integrated technologies support the safe and commercial-scale deployment of CO_2 storage.

3.2.4. Post-Injection Monitoring and Leakage Prevention

The prevention and control of CO_2 leakage in geological storage depend on a comprehensive, full-lifecycle monitoring system. CO_2 migration can cause environmental risks like soil acidification, groundwater contamination, and ocean acidification. Measurement-Monitoring-Verification (MM&V) technologies are vital for tracking subsurface CO_2 behavior and preventing leaks [16] [28]. The monitoring framework is composed of three main components. Environmental monitoring involves techniques such as lidar and isotopic tracing to detect atmospheric and near-surface anomalies. Safety monitoring includes microseismic surveillance and wellbore integrity assessments to ensure operational safety. Migration monitoring relies on methods like time-lapse seismic imaging and vertical seismic profiling to track CO_2 movement underground [15] [16] [29]. Monitoring is conducted throughout the entire project lifecycle. It begins with baseline assessments, continues through operational tracking, and extends into post-closure monitoring. Different technologies are applied at each stage. For example, downhole sensors are commonly used during the injection phase, while satellite-based remote sensing is more suited to post-closure surveillance. The integration of these techniques effectively mitigates leakage risks and ensures the long-term stability of CO_2 storage systems.

3.3. Policy and Support Systems

3.3.1. Policy Incentives

Global policies drive CCUS industrialization through carbon pricing, tax incentives, and infrastructure investment. The U.S. 45Q tax credit provides $35/ton for EOR and $50/ton for geological storage [30]. Norway's carbon tax (590 - 2000 NOK/ton) supports Sleipner's saline storage [31]. The UK's £1 billion fund targets four storage hubs by 2030, and the EU's Horizon program backs cross-border infrastructure. Global CCUS investment exceeded $6 billion by 2023 [32]. China's CCUS policy began with the 2008 climate strategy, added CCUS to green financing in 2020, and mandated low-cost innovation and demonstrations in 2021. These policies enabled the Qilu-Shengli million-ton CCUS project, supporting dual-carbon goals [5] [33].

3.3.2. Standards and Normative Systems

Standardized accounting and technical frameworks ensure emission reduction credibility. Internationally, the IPCC's 2006 Guidelines outline carbon accounting for CCUS, while the CO_2 Capture, Transport, and Storage Technical Committee uses lifecycle assessment to quantify reductions, setting verification standards [34] [35]. Canada's Quest project defines accounting boundaries, and Chinese researchers developed a storage model for Shengli Oilfield [34]-[37]. Technical standards include the EU's Directive 85/337/EEC for capture safety, Norway's CO_2 pipeline guidelines, and Canada's Z-741 for saline aquifer storage [38]-[40]. These standards span the CCUS chain, supporting carbon market trading and scalability.

3.3.3. Legal and Regulatory Frameworks

A robust legal and regulatory framework ensures CCUS safety, project consistency, and carbon market stability, with notable regional differences. The EU's Directive 2009/31/EC sets storage permitting rules, enhanced by Directive (EU) 2018/2001 for full-chain oversight [41] [42]. The UK's 2008 Energy Act and 2011 CO_2 Storage Regulations cover all storage types [43] [44]. The US regulates via the Clean Air Act, with California's LCFS enabling market integration. Australia uses a federal-state model for balanced regulation [45] [46]. These frameworks prioritize environmental risk management, market compatibility, and cross-border cooperation, supporting CCUS scalability through clear accountability and risk-sharing.

4. Challenges for CGUS in China's Oil and Gas Industry

4.1. Economic Constraints

Carbon Capture, Utilization, and Storage (CCUS) faces significant economic challenges due to high costs and the lack of a viable business model. CO_2 capture from low-concentration sources (e.g., coal-fired power plants, steel mills) costs 300 - 900 CNY/ton, with transportation adding 0.9 - 1.4 CNY/(ton·km) [14] [15]. CO_2-enhanced oil recovery can offset some costs, but project economics are limited by reservoir conditions, source proximity, and technological maturity, leading to long payback periods [47]. Cross-industry collaboration is hindered by unclear revenue sharing, responsibility allocation, and risk-sharing mechanisms. No mature commercial model exists. Policy support is lacking, with no targeted fiscal incentives (e.g., storage subsidies, carbon tax exemptions) and insufficient carbon market certification for CCUS emission reductions, failing to address high project risks [14].

4.2. Technological Bottlenecks

CCUS faces three key technical challenges. First, storage potential assessments lack precision, relying on static parameters like porosity and permeability without integrating 3D geological and dynamic flow analyses, limiting site selection for large-scale projects [16] [31]. Second, large-scale CO_2 injection risks reservoir damage from salt precipitation and clogging, as seen in the Gorgon project's injection well failures, exposing reliability issues [15] [18] [48]. Third, long-term monitoring systems are underdeveloped, with onshore methods relying on costly seismic techniques and offshore monitoring limited by complex conditions and sensor constraints, creating economic and sustainability challenges for post-closure monitoring [32] [47] [49] [50].

4.3. Weak Support Systems

Institutional barriers impede CCUS industrialization. Current environmental and energy laws do not address CCUS-specific needs, lacking clear accountability for risks like storage leakage and standardized approval processes, increasing compliance costs [14] [47]. Carbon market integration lacks dedicated legislation, hindering revenue generation. Carbon accounting is flawed, with unclear guidelines reducing transparency and accuracy. Inaccuracies in measuring CO_2 emissions from enhanced oil recovery and ambiguous standards for equipment-related emissions lead to inflated reduction claims, undermining carbon market credibility [14] [45].

5. Recommendations for CGUS Development in China

Drawing on the analysis of domestic and international CGUS industry experiences, we propose a comprehensive set of recommendations to advance China's CGUS development. These recommendations address economic, technical, and institutional challenges while balancing the perspectives of key stakeholders, including oil companies seeking profitability through innovative business models, regulators ensuring compliance and decarbonization through robust legal frameworks, and communities prioritizing environmental safety and economic benefits through transparent engagement. By fostering market-oriented commercialization, advancing technological and monitoring innovations, and establishing supportive institutional systems, these strategies aim to align with China's dual-carbon goals and promote sustainable, high-quality CGUS growth.

5.1. Commercialization Framework

To overcome economic barriers, a market-oriented framework combining policy, industry, and business models is needed. Policies should include cost-sharing mechanisms, tax exemptions for CO_2-enhanced oil recovery (EOR), and a multi-billion CNY CCUS fund for pipeline and storage R&D to reduce risks and boost participation [5] [18]. Industrially, million-ton CCUS clusters in regions like Ordos and Songliao should use shared capture, co-built transport, and centralized storage to cut costs. Business models can pilot carbon storage subscriptions (e.g., Shell's "ton-carbon custody") and dual-revenue streams from low-carbon crude certification and carbon credit trading, enabling oil companies to become carbon asset managers [14]. To address community concerns, CCUS projects should emphasize transparent communication and proactive stakeholder engagement to mitigate perceived environmental risks. Community-focused measures, such as local job creation through infrastructure development and revenue-sharing from carbon credit markets, can further enhance regional economic benefits and foster public support.

5.2. Technological and Monitoring Advancements

CCUS scalability requires innovation in technology and monitoring. A new evaluation system integrating static geological parameters (porosity, permeability) with dynamic flow responses should improve site selection accuracy [20]. Storage engineering must optimize well layouts, injection pressures, and capacities to prevent reservoir damage. Monitoring upgrades need high-precision, real-time tools like fiber-optic systems and geophysical devices, tailored to terrestrial and offshore conditions, with 3D networks for leak detection and cost-efficient lifecycle monitoring [32]. Disruptive technologies like CO_2 mineralization and bioconversion should be explored for long-term storage safety.

5.3. Institutional Support Systems

A robust legal and standards framework is essential. A Carbon Storage Management Law should clarify subsurface rights, saline aquifer access, and project approvals, with clear responsibilities and lifelong liability for leaks. Standards must address capture energy limits, transport specifications, and storage integrity [5]. Refined carbon accounting should standardize EOR emissions calibration and equipment emission deductions for global carbon market compatibility. Legal and technical synergy can resolve environmental risks, market integration, and international cooperation barriers, supporting CCUS industrialization.

6. Conclusions

(1) Strategic Role of CGUS in Oil and Gas Decarbonization: Carbon Geological Utilization and Storage (CGUS) is a critical technology for the oil and gas industry's low-carbon transition. Amid global carbon neutrality efforts, CGUS has evolved from a supplementary tool to a cornerstone of decarbonization, offering emission reduction and resource enhancement. International oil majors have leveraged early advantages to establish commercial CGUS projects in regions like the North Sea and Gulf of Mexico, with mature technical and business models. Despite a later start, China's rapid progress in CO_2-enhanced oil recovery (EOR) demonstrates significant market potential.

(2) Global CGUS Synergy: Global CGUS advancement benefits from a policy-technology-institutional framework. Policies integrate fiscal incentives, dedicated

funds, and carbon market linkages. Technological progress spans reservoir assessment to long-term monitoring, enhancing safety and cost-effectiveness. Standardized systems and legal frameworks remove institutional barriers, supporting large-scale CGUS deployment.

(3) China's CGUS Challenges: China's CGUS faces three key barriers: high lifecycle costs, requiring industrial clusters, shared infrastructure, and policy support; technical limitations, needing dynamic geological assessments, optimized engineering, and advanced monitoring; and institutional gaps, requiring accelerated legislation, comprehensive standards, and carbon market integration. A synergistic commercial, technical, and institutional framework can drive transformative CGUS progress, supporting China's dual-carbon goals.

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Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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