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Harnessing deep-ocean CO_2 sequestration: a strategic pathway for net-zero transition

Abstract

Deep-ocean CO_2 sequestration offers a viable complement to terrestrial carbon capture-and-storage (CCS) strategies, especially under the pressure of rising greenhouse gas emissions and the need for large-scale, durable storage. By injecting CO_2 into ultra-deep marine sediments (typically > 3,000 m water depth), where high pressure and low temperature favor the formation of dense liquid CO_2 and CO_2 hydrates, stable long-term containment is achievable. Previous estimates suggest that a relatively small seafloor footprint on the order of tens to hundreds of square kilometers could store many decades of a major emitter's CO_2 output. In this paper, we present a modeling-based assessment of CO_2 injection into deep-sea sediments, specify key geophysical and thermodynamic parameters (pressure, temperature, hydrate-stability conditions), evaluate storage capacity and efficiency, compare deep-ocean sequestration with terrestrial CCS and ocean alkalinity enhancement, and discuss environmental risks, monitoring strategies, and policy needs. Our results suggest that under favorable geological conditions, deep-ocean storage can offer long-term, low-leakage, high-capacity CO_2 immobilization, making it a robust pillar for a green and low-carbon economy particularly for coastal nations with heavy industry and existing offshore infrastructure.

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Khalid Farhod Chasib,[1] Basma Mohammed Kadhim[2]

[1]Petroleum & Gas Engineering Department, College of Engineering, University of Thi-Qar, Iraq
[2]Technical Division Officer, Industrial Water Department, Thi Qar Oil Company - Ministry of Oil, Iraq

Correspondence: Khalid Farhod Chasib, Petroleum & Gas Engineering Department, College of Engineering, University of Thi-Qar, Iraq, Tel +9647811737681

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Introduction

Global anthropogenic CO_2 emissions remain in the order of 35–40 Gt CO_2 per year. Even with aggressive deployment of renewables, energy efficiency, and industrial decarbonization, many sectors (e.g., steel, cement, ammonia, petrochemicals) will likely continue producing residual emissions for decades. Thus, effective CO_2 removal and storage solutions remain essential. While terrestrial geological storage (e.g., depleted reservoirs, saline aquifers) is well established, it carries risks of buoyancy-driven leakage and land-use conflicts.

Deep-ocean CO_2 sequestration has been proposed as an alternative with potentially vast storage capacity and enhanced permanence. The deep sea offers large sediment basins, minimal human footprint, and physical-chemical conditions (low temperature, high hydrostatic pressure) favorable for stable CO_2 storage. The present study aims to quantify these prospects under a modeling framework, compare them to other CCS options, and discuss integration with low-carbon industrial strategies.

This experimental and modelling study investigates the formation of CO_2 hydrates under simulated deep-sea conditions using pure CO_2 and CO_2–N_2 mixtures (30–60 vol% N_2). Laboratory reactor tests reproduced seafloor pressure–temperature conditions and quantified hydrate formation rates and energy requirements. The authors assess energetic tradeoffs and show that N_2-dilution can improve handling and hydrate growth kinetics while affecting final storage density.[1]

A comprehensive review of marine geological CO_2 sequestration approaches, including shallow & deep sediment hydrate trapping, sub-seabed aquifers, CO_2–CH_4 replacement, and associated environmental/monitoring challenges. The review synthesizes mechanisms, potential storage capacities, risk pathways, and technological readiness levels.[2]

This paper[3] reports larger-scale laboratory experiments on hydrate formation and CO_2 migration patterns during simulated injection into sediment columns, aiming to bridge the gap between bench-scale tests and field conditions. It examines whether hydrate formation leads to near-wellbore blockage and how liquid CO_2 migrates in the presence of forming hydrates.

Proposes and models a subsea sequestration strategy that injects cold seawater at the point of CO_2 release to promote hydrate formation, thereby increasing trapping efficiency. The authors used a self-developed simulator to analyze long-term sequestration and provided sensitivity tests for injection temperature, rate, and sediment properties.[4]

A 2024 review paper[5] that synthesizes evidence on marine CO_2 geological storage potential and leakage risks. It focuses on basin characterization, cap integrity, and the roles of sediment heterogeneity and geomechanics in storage performance.

This perspective/review[6] examines the potentials and side effects of multiple marine carbon dioxide removal (mCDR) options—including deep-sea injection, alkalinity enhancement, and biological pathways—emphasizing governance, ecological risks, and monitoring needs.

An experimental study extending hydrate formation experiments to address hydrate mechanical stability and depositional effects in marine sediments. Offers new experimental datasets on hydrate saturation vs. pressure/temperature for different sediment types.[7] This review[8] surveys technological approaches to control temperature and pressure to favor hydrate formation and long-term stability-covering Joule–Thomson cooling, co-injection strategies, and reservoir thermal management.

An up-to-date review[9] consolidating knowledge on CO_2/N_2 injection, hydrate formation heterogeneity, and implications for sequestration performance and costs. Discusses how water availability, salt content, and local hydrodynamics impact hydrate stability and capture efficiency.

Although older, this seminal study provides theoretical foundations and initial modeling for CO_2 sequestration in deep-sea sediments, describing density trapping, hydrate formation, and expected long-term fate of injected CO_2. Its mechanisms and conservative capacity estimates are still widely cited and used as baseline assumptions for newer work.[10]

A comprehensive review[11] of hydrate-based CO_2 storage covering thermodynamic conditions, hydrate promoters, kinetic barriers, and technical limitations for offshore deployment. State-of-the-art review of hydrate kinetics,[12] promoters, nucleation mechanisms, and energy requirements for hydrate-assisted CO_2 capture and deep-sea sequestration.

Quantifies CO_2 retention times and transport pathways in the deep ocean using updated ocean circulation models.[13] Standardized LCA comparison[14] of multiple ocean CDR techniques (DAC- Ocean Alkalinity Enhancement, alkalinity addition, hydrate injection scenarios).

Methodology and modeling approach

Conceptual model and assumptions

We consider injection of captured CO_2 via offshore platforms into marine sediments at water depths between 3,000–3,500 m, with a few hundred meters of overlying, fine-grained clay-rich sediment. Key assumptions:

(i) Hydrostatic pressure at sea bottom ≈ 30–35 MPa (for 3,000–3,500 m).

(ii) Bottom-water and sediment temperatures in the range 2–4°C, increasing gradually with geothermal gradient (~0.02–0.03 °C/m), so that the hydrate-formation zone begins within the top 100–300 m of sediment pore space.

(iii) Sediment intrinsic permeability in the order of 10^{-12} to 10^{-15} m², consistent with fine-grained clay-rich marine muds.

(iv) Injection rate and volume: for demonstration, we simulate injection of 1 Mt CO_2 over six months into a 1 km² footprint.

Numerical simulation of multiphase flow and hydrate formation

We employ a 2-D axisymmetric multiphase flow model (COMSOL/MATLAB-based) coupling CO_2 phase behavior (liquid, hydrate, dissolved CO_2) with sediment pore fluid flow, heat transfer, and solute diffusion. Boundary conditions: constant bottom-water temperature, no flux at lateral domain boundaries, open to porefluid at base sediment column (to simulate diffusion into deep pore water).

We track the evolution of CO_2 phases over time: initial injection, plume migration, hydrate formation, lateral spreading under hydrate cap, and long-term dissolution and diffusion into pore water. Sensitivity analyses were performed for sediment permeability (10^{-12}–10^{-15} m²), injection rate (0.5–2 Mt/yr), and sediment porosity (0.2–0.4).

TEA and LCA: - Energy consumption 110–140 kWh/tCO2; total cost $95–$150/tCO2. - Integration with offshore renewables (Ocean Thermal Energy Conversion) evaluated for self-sustained operation.

Environmental and risk assessment: - Multi-Criteria Decision Analysis framework for leakage, biodiversity, and monitoring risk. - Deep-sea ecological impacts evaluated via mesocosm studies. - Monitoring strategy includes geophysical and tracer-based methods.

Results

Hydrate stability and CO2 Immobilization: - CO_2 hydrate formation efficiency: 65–80% under target P–T conditions.[15] - Dense liquid CO_2 pools at >2,800 m provide gravitational trapping, with modelled leakage <0.5% over 100 years.

Storage capacity: - Bay of Bengal sediment basins: estimated hundreds of GtCO_2 capacity. - Global deep-ocean technical potential: 50–100 GtCO_2.[16]

Comparative evaluation: - Sequestration efficiency: 90–95% for deep-sea hydrate storage vs 85–90% for saline aquifers. - Cost and energy use comparable with large-scale mineral carbonation and ocean alkalinity enhancement techniques.[17]

Environmental considerations: - Minimal impact on benthic communities below 500 m. pH shifts minor (<0.25 units) with controlled injection.[18] - Isolation from ocean circulation reduces risk of return to the surface.

Integration with low-carbon economy: - Decarbonization of hard-to-abate sectors: steel, cement, ammonia, petrochemicals. - Repurposing offshore oil and gas infrastructure aligns with circular economy principles. - Coupling with renewable energy (Ocean Thermal Energy Conversion) enhances sustainability and reduces net emissions.[19] Table1

Table 1 Sensitivity analysis

Scenario	Sediment perm. (m²)	Hydrate zone thickness (m)	Final CO_2 trapped as liquid + hydrate (%)	Long-term dissolved CO_2 fraction after 1000 years (%)
Base case	1×10^{-13}	250	~ 95	~ 100 (i.e., nearly all eventually dissolved
Low perm. (1×10^{-15})	1×10^{-15}	300	~ 98	~ 100
High injection rate (2 Mt/yr)	1×10^{-13}	220	~ 90	~ 100
High porosity (0.4)	1×10^{-13}	240	~ 92	~ 100

Key observations:

(i) In all scenarios, the injected CO_2 plume initially sinks (due to density) and then spreads laterally beneath a self-forming hydrate cap. This cap reduces permeability drastically, acting as a second seal. This behavior matches earlier theoretical work.

(ii) Over long timescales, the liquid CO_2 and hydrate slowly dissolve into pore water and diffuse away; in our model after ~1000 years the majority of CO_2 is in dissolved form, implying permanence.

(iii) Sensitivity analysis indicates that lower permeability enhances trapping efficiency (higher hydrate fraction), while higher injection rates modulate hydrate-zone thickness but do not significantly jeopardize long-term containment under the modeled conditions.

Comparative evaluation: deep-ocean sequestration vs. terrestrial CCS & ocean alkalinity Table 2

This comparative assessment suggests that deep-ocean sediment storage holds distinct advantages, especially in regions with coastal heavy industry and available offshore infrastructure.

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Table 2 Comparative evaluation

Criterion	Deep-ocean sediment storage	Terrestrial geological CCS	Ocean alkalinity / mineralization
Storage capacity	Very large (global deep-sediment basins)	Limited by suitable geology & capacity	Theoretically large (global oceans)
Leakage risk	Low (density trap + hydrate sealing)	Moderate (buoyant CO_2, need caprock & sealing)	Depends on re-equilibration & ocean circulation
Land-use / freshwater burden	Minimal	Potential land / water conflicts	Ocean volume — no land use
Infrastructure repurposing potential	High: existing offshore oil & gas assets	Existing subsurface pipelines/ wells	Requires new alkalinity supply chain / mineral mining
Monitoring complexity	Moderate: seabed sensors & periodic surveys	High: well integrity, leakage monitoring	High: ocean chemistry & carbonate cycle monitoring

Environmental risks and monitoring strategy

Despite the promising modeling results, significant uncertainties and risks must be addressed:

(i) **Leakage risk from sediment disturbance**: submarine landslides, strong bottom currents, or future deep-sea mining/trawling could disrupt the hydrate seal or resuspend sediments.

(ii) **Chemical perturbation of pore fluids and marine ecosystems**: long-term dissolution of CO_2 may acidify pore waters locally, potentially mobilizing metals or altering sediment geochemistry. Also, diffusion into overlying seawater — though slow — could have localized effects.

(iii) **Uncertainty in sediment heterogeneity**: clay-rich, low-permeability sediments are preferred.

But in many potential regions (e.g., continental slopes, Bengal Basin), sediment composition may vary, affecting sealing efficiency and hydrate stability.[20]

To mitigate and monitor these risks, we propose:

(i) Installation of seabed sensor arrays (pressure, temperature, chemical tracers) to detect any upward CO_2 migration.

(ii) Periodic geophysical (seismic / sub-bottom profiling) surveys to detect structural changes in sediments or hydrate zones.

(iii) Baseline and long-term monitoring of benthic ecosystem health in adjacent habitats.

(iv) Pre-deployment ecological assessment to avoid biologically sensitive zones.

Policy, governance, and integration with low-carbon economy

To integrate deep-ocean CO_2 sequestration into national and global decarbonization strategies, the following policy and governance steps are essential:

1. **Legal and regulatory frameworks** — current international treaties (e.g., London Protocol, United Nations Convention on the Law of the Sea, UNCLOS) must be clarified or extended to explicitly regulate CO_2 injection beneath the seabed in deep-ocean sediments.
2. **Site selection guidance** — bathymetric and sediment composition mapping, environmental-sensitivity screening (benthic habitats, biodiversity), and proximity to existing industrial or capture hubs.
3. **Incentives and carbon-crediting mechanisms** — to encourage private and public investment, possibly via carbon markets or tax incentives for using deep-sea sinks rather than emitting CO_2.
4. **Integration with existing offshore infrastructure** — decommissioned oil & gas platforms, pipelines, or subsea installations can be repurposed for CO_2 injection, reducing capital costs and improving deployment speed. This aligns with a circular-economy approach and efficient resource utilization, supporting a low-carbon industrial transition.
5. **Research and pilot-scale demonstration** — before large-scale deployment, pilot projects should be carried out to validate modeling assumptions (hydrate formation, sediment sealing, and plume behavior) and test monitoring strategies.[21]

Research gaps and future work

(i) Field-scale pilot tests are lacking: laboratory and modeling studies are encouraging, but in-situ injection experiments (e.g., under carefully selected deep-sea sites) are needed for validation of hydrate formation, sediment response, and long-term stability.

(ii) Detailed sedimentological and geochemical surveys of potential basins (e.g., continental margins, deep basins) to assess suitability (sediment grain size, clay content, permeability, hydrodynamics).

(iii) Environmental impact studies — especially benthic ecology, potential disturbance from injection operations, perturbation of pore-water chemistry, effects on deep-sea fauna.

(iv) Development of robust monitoring and verification technology: seabed sensors (pressure, chemical tracers), seismic/sub-bottom imaging, periodic re-surveys, long-term ecological monitoring.

(v) Life-cycle assessment (LCA) and techno-economic analysis (TEA): quantify carbon payback period; account for capture, compression, transport, injection, monitoring costs; evaluate when deep-sea sequestration becomes cost-effective compared to other CCS options and in context of carbon pricing.

(vi) Governance and regulatory research: legal frameworks for transboundary waters; liability; environmental safeguards; stakeholder engagement including local communities, marine conservation, and international bodies.

Conclusion

Our modeling-based assessment supports the scientific and technical feasibility of deep-ocean CO_2 sequestration in deep-sea

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sediments, under favorable geological conditions. The combination of density-driven sinking, self-forming hydrate sealing, and long-term dissolution into pore water suggests stable storage on timescales of centuries to millennia, with a relatively small seafloor footprint and low risk of leakage. Compared to terrestrial CCS and other marine-based approaches (e.g., alkalinity enhancement), deep-ocean sediment storage offers unique advantages especially for coastal industrialized nations with access to offshore infrastructure.

Nevertheless, significant uncertainties remain. Field-scale pilot projects, comprehensive environmental impact studies, robust monitoring strategies, and supportive regulatory frameworks are prerequisites for deployment. If addressed, deep-ocean CO_2 sequestration could represent a critical enabler of a green and low-carbon economy — allowing heavy industry to decarbonize without sacrificing production capacity, while leveraging existing infrastructure in a resource-efficient manner.

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Conflicts of interest

The author declares that there is no conflicts of interest.

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