

Geological Carbon Sequestration: A Review of Storage Mechanisms, Risks and Opportunities

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Abstract

Climate change mitigation requires significant reductions in greenhouse gas emissions, and geological carbon sequestration (GCS) is a critical technology for achieving this goal. GCS involves capturing CO₂ from industrial sources and injecting it into subsurface rock formations for long-term storage. The technology has the potential to reduce emissions from industrial sources, but its effectiveness depends on a thorough understanding of storage mechanisms, risks, and opportunities. Geological formations such as depleted oil and gas fields, saline aquifers, and coal seams can store CO₂, but each has its own unique characteristics and challenges. A comprehensive review of GCS is necessary to understand the current state of knowledge, identify knowledge gaps, and inform policy and regulatory decisions. This review highlights the potential of geological carbon sequestration (GCS) as a critical technology for reducing greenhouse gas emissions. Key findings include the importance of understanding storage mechanisms, risks, and opportunities associated with CO₂ injection into subsurface formations. The review identifies depleted oil and gas fields, saline aquifers, and coal seams as promising storage sites. However, knowledge gaps remain in site characterization, fluid flow, and monitoring techniques. In conclusion, GCS can play a vital role in mitigating climate change, but further research is needed to overcome technical challenges and ensure safe and effective storage of CO₂.

Keywords: Carbon sequestration, CO₂ storage, Subsurface trapping, Climate, Carbon Capture and Storage (CCS), and Decarbonization.

Significance of the Study: The significance of this study on "Geological Carbon Sequestration: A Review of Storage Mechanisms, Risks and Opportunities" lies in its contribution to addressing one of the most pressing global challenges, climate change. As atmospheric carbon dioxide (CO₂) levels continue to rise due to industrialization and fossil fuel combustion, geological carbon sequestration (GCS) offers a promising strategy for long-term carbon management. This review provides a comprehensive understanding of how CO₂ can be safely captured and stored in deep geological formations such as depleted oil and gas reservoirs, saline aquifers, and unmineable coal seams.

By analyzing various storage mechanisms and evaluating associated risks, including leakage, induced seismicity, and groundwater contamination, the study enhances awareness of the scientific, technical, and environmental factors governing successful GCS implementation. Moreover, it identifies the opportunities for optimizing storage efficiency and integrating GCS with renewable and industrial carbon utilization technologies. The findings of this review are significant for policymakers, environmental scientists, and energy industries seeking sustainable pathways toward

carbon neutrality. Ultimately, this study supports global climate mitigation efforts by promoting safer and more effective geological storage strategies that can complement other carbon reduction initiatives and contribute to achieving international climate targets.

Introduction

The accelerating pace of global climate change, driven largely by anthropogenic greenhouse gas (GHG) emissions, represents one of the most profound environmental challenges confronting modern civilization [1]. Atmospheric concentrations of carbon dioxide (CO₂) have surged from pre-industrial levels of approximately 280 ppm to over 420 ppm in 2024, largely due to fossil fuel combustion, industrial processes, and deforestation [2]. This escalation has intensified the frequency of extreme weather events, disrupted ecosystems, and exacerbated socioeconomic vulnerabilities across the world [3]. To limit global temperature rise to within 1.5 °C, as articulated in the Paris Agreement, effective carbon management strategies have become indispensable [4]. These strategies encompass both emission reduction and carbon removal approaches, emphasizing the urgent necessity of scalable

technologies capable of achieving deep decarbonization[5].

Carbon sequestration, the process of capturing and storing atmospheric CO₂ in natural or engineered sinks, has emerged as a critical pillar in climate mitigation efforts [6]. It encompasses both biological methods, such as afforestation, and technological interventions, such as carbon capture and storage (CCS) [7]. Among these, geological carbon sequestration (GCS) offers a uniquely durable solution by storing CO₂ deep underground in stable geological formations for thousands to millions of years. The approach provides the dual advantage of mitigating emissions from hard-to-abate industrial sectors such as cement, steel, and chemical manufacturing while supporting a gradual energy transition toward renewables [8]. Its compatibility with carbon capture and utilization (CCU) further enhances its potential as a bridge technology for net-zero pathways.

The geological storage of CO₂ involves injecting compressed, supercritical CO₂ into suitable subsurface formations such as deep saline aquifers, depleted hydrocarbon reservoirs, and unmineable coal seams, typically at depths greater than 800 m. Under such conditions, CO₂ remains trapped through a combination of physical and geochemical mechanisms that prevent its migration to the surface. Successful commercial-scale projects, including the Sleipner field in Norway, the Weyburn-Midale project in Canada, and the Gorgon project in Australia have demonstrated the technical and environmental feasibility of long-term CO₂ storage [9]. These field experiences have provided crucial insights into reservoir integrity, monitoring methodologies, and the operational economics of large-scale implementation. Despite this progress, concerns over leakage potential, induced seismicity, and public acceptance remain persistent, underscoring the need for transparent governance and continuous technological innovation[10].

Over the past two decades, CCS technologies have evolved from pilot-scale demonstrations to integrated industrial systems combining capture, transportation, injection, and monitoring components. Advances in membrane separation, cryogenic capture, and solvent regeneration have significantly improved energy efficiency, while digitalization and artificial intelligence (AI) are transforming monitoring and predictive modeling [11]. These innovations are complemented by policy incentives such as carbon pricing, tax credits, and emissions trading schemes that enhance project bankability[12]. Nevertheless, the high capital cost of CCS deployment, coupled with fragmented regulatory frameworks, continues to hinder rapid global adoption [13]. Therefore, integrating technological innovation with coherent policy and public engagement remains vital for the long-term success of geological sequestration initiatives.

The primary purpose of this review is to provide a comprehensive and integrative assessment of geological carbon sequestration (GCS) as a cornerstone strategy for achieving long-term carbon neutrality and climate stabilization.

It aims to synthesize current scientific knowledge on the principles, mechanisms, and effectiveness of CO₂ storage in geological formations while critically analyzing associated technical, environmental, and socio-economic dimensions. The review emphasizes a multidisciplinary perspective that bridges geological sciences, engineering innovations, environmental policy, and sustainable development frameworks. By doing so, it highlights how GCS complements other decarbonization pathways, including renewable energy deployment, carbon capture and utilization (CCU), and negative-emission technologies. This paper encompasses both theoretical foundations and empirical evidence from global field projects, addressing key aspects such as trapping mechanisms, site selection criteria, reservoir integrity, and long-term monitoring strategies. It further evaluates potential risks such as leakage, induced seismicity, and public perception and explores recent advances in monitoring, modeling, and artificial intelligence that enhance operational safety and efficiency. The review also investigates the economic, policy, and regulatory frameworks underpinning large-scale deployment, with attention to global initiatives aligned with the Paris Agreement and net-zero targets. Finally, it identifies persisting challenges, knowledge gaps, and future research directions necessary for the safe, efficient, and socially acceptable implementation of GCS. Through this synthesis, the paper seeks to inform policymakers, researchers, and industry stakeholders on the pathways toward sustainable and scalable carbon storage solutions.

Overview of Geological Carbon Sequestration (GCS)

Geological carbon sequestration (GCS) is a scientifically validated and technologically feasible approach for the long-term isolation of carbon dioxide (CO₂) from the atmosphere through its injection into deep underground formations. It represents a key component of the broader carbon capture and storage (CCS) chain, which aims to mitigate anthropogenic greenhouse gas emissions and support the transition toward net-zero carbon economies [14, 15]. In principle, GCS exploits the natural storage capacity of subsurface geological systems by injecting CO₂ at depths typically greater than 800 meters, where high-pressure and temperature conditions maintain CO₂ in a supercritical phase, allowing it to behave both as a gas and a liquid[16]. The process relies on a combination of physical and geochemical trapping mechanisms that immobilize CO₂ over extended geological timescales, ensuring its long-term stability and minimizing leakage risks[17].

Several types of geological formations have been identified as suitable for CO₂ storage. Deep saline aquifers are considered the most abundant and promising option due to their vast capacity and saline nature, which prevents interference with freshwater resources[18]. Depleted oil and gas reservoirs, on the other hand, offer proven structural integrity and existing infrastructure, significantly lowering operational costs.

Unmineable coal seams provide additional storage potential through CO₂ adsorption on coal surfaces, although permeability reduction remains a technical challenge. Moreover, basaltic and shale formations are gaining attention for their ability to chemically react with CO₂, forming stable carbonate minerals that ensure permanent sequestration [19]. The choice of storage formation is typically governed by geological, hydrological, and economic factors, including reservoir porosity, permeability, caprock integrity, and proximity to emission sources.

Globally, several large-scale projects have demonstrated the practicality of GCS. Notable examples include Sleipner and Snøhvit in Norway, Weyburn-Midale and Quest in Canada, and Gorgon in Australia, all of which have successfully stored millions of tonnes of CO₂ and provided valuable insights into reservoir performance, monitoring, and long-term containment [20]. Additional projects in China, the United States, and the Middle East reflect an expanding global adoption of GCS as part of national climate strategies [21]. Despite these advancements, the cumulative global storage capacity utilized remains less than 0.1% of the total estimated geological potential, highlighting the need for greater investment, policy coordination, and technological innovation [22].

From a technical perspective, GCS is well proven, but its large-scale economic deployment depends on cost reductions, policy incentives, and infrastructure integration. The storage process itself generally accounts for a small fraction of total CCS costs, while capture and compression dominate overall expenses [23].

Recent progress in well design, geophysical monitoring, and digital modeling has enhanced injection efficiency and reduced uncertainty [24]. Economically, mechanisms such as carbon pricing, emission trading systems, and tax credits, particularly the U.S. 45Q and the EU Emissions Trading Scheme, are improving project feasibility and encouraging private sector engagement. When integrated with enhanced oil recovery (EOR) and low-carbon hydrogen production, GCS could further accelerate its commercial viability and contribute meaningfully to achieving global decarbonization goals [25].



Figure 1. Current worldwide CO₂ geological storage projects

Source: [13]

In summary, geological carbon sequestration represents a mature and scalable technology with vast global potential for mitigating CO₂ emissions. Continued innovation in reservoir characterization, monitoring, and economic frameworks will be essential to expand deployment and ensure GCS fulfills its pivotal role in sustainable carbon management.

Table 1. Major operational and landmark CO₂ storage projects (key metrics)

Project (operator)	Country	Approx. annual injection (Mt CO ₂ /yr)	Storage formation type	Operational Start	Notes / monitoring	Citation
Sleipner (Equinor)	Norway	~1.0	Utsira saline sandstone (offshore)	1996	Long-term 4D seismic monitoring; no detected leakage	[14]
Weyburn-Midale (IEA projects)	Canada	~2–3 (EOR operations; cumulative larger)	Depleted carbonate/reservoir (EOR)	2000 (EOR expansion/monitoring since 2000s)	Extensive monitoring and geochemical tracing under IEA MW project.	[15]
Gorgon CO ₂ Injection (Chevron/Gorgon JV)	Australia	3.3–4.0 (design)	Deep saline (Dupuy Formation)	2019 (injection commenced)	Large-scale offshore injection with dedicated monitoring program	[16]
Illinois Basin — Decatur (ADM/DOE)	USA	~1.0 (injection campaign ≈1 Mt total/year)	Mount Simon Sandstone (deep saline)	2011 (pilot/demonstration)	Intensive field characterization and monitoring; microseismic studies	[17]

CO₂ Storage Mechanisms in Geological Formations

The secure long-term storage of CO₂ in the subsurface relies on multiple, interacting trapping mechanisms that successively immobilize injected carbon and reduce its mobility over time. These mechanisms, structural (or stratigraphic) trapping, residual (capillary) trapping, solubility trapping, and mineral trapping, act over different spatial and temporal scales to enhance containment. Understanding their interplay and constraints is crucial to assessing storage security, capacity, and performance [26].

Structural and Stratigraphic Trapping

When CO₂ is injected into a formation, it initially behaves as a mobile buoyant phase and migrates upward until it encounters impermeable barriers, such as caprocks or geological seals.

This structural and stratigraphic trapping is often the primary mechanism that prevents CO₂ from escaping the reservoir and is analogous to oil/gas entrapment in conventional hydrocarbon systems [27]. The caprock's integrity, fault sealing behavior, and stratigraphic layering determine how effectively the plume remains confined during the early phases [28].

Residual (Capillary) Trapping

As the plume advances, residual trapping immobilizes portions of CO₂ within pore spaces. In this process, CO₂ becomes disconnected into droplets or ganglia held by capillary forces when brine imbibes into the pore network. Residual trapping is especially important during migration and helps reduce the mobile fraction of the CO₂ plume. The effectiveness of this mechanism is controlled by pore structure,

wettability, and hysteresis in relative permeability [29].

Solubility Trapping

Over longer time scales, solubility trapping becomes more dominant. CO₂ dissolves into the brine (formation water), reducing its buoyancy and allowing it to spread through diffusion and density-driven convection, which accelerates mixing. Solubility trapping thereby converts free-phase CO₂ into a denser aqueous form less likely to migrate upward. The rate and extent of dissolution depend on temperature, pressure, salinity, and formation heterogeneity [30].

Mineral Trapping and Geochemical Processes

In favorable geological settings, mineral trapping can permanently fix CO₂ by forming carbonate minerals through reactions between dissolved CO₂ and reactive host rock minerals [31, 32]. Although slower than physical and solubility processes, mineral trapping provides ultimate sequestration security. For instance, increased concentrations of minerals such as anorthite can boost mineralization rates, though high salinity can inhibit CO₂ dissolution and thereby slow subsequent mineral trapping [33].

Modeling and Simulation of Storage Processes

Numerical modeling and simulation are essential to quantify the contributions of these mechanisms, predict plume behavior, and optimize injection strategies. Frameworks that integrate structural, capillary, solubility, and mineral trapping dynamics over time enable scenario assessments for storage performance and risk [34]. In benchmark studies, models parameterize essential trapping physics to simulate CO₂ migration, dissolution, and residual trapping in heterogeneous formations [35].

Table 2. CO₂ trapping mechanisms: description, timescale, role in permanence

Trapping mechanism	Mechanisms summary	Dominant timescale	Role in long-term permanence	Key Citations
Structural/stratigraphic	Physical accumulation beneath impermeable caprock or sealed closure	Immediate → decades	First line of containment; prevents buoyant migration	[6]
Residual (capillary)	Capillary forces trap disconnected CO ₂ ganglia in pore space	Years → centuries	Converts mobile CO ₂ to immobile phase; reduces mobile fraction	[14]
Solubility	Dissolution of CO ₂ into formation brine; dense plume forms and convects	Decades → centuries	Reduces buoyancy; promotes dispersion and security	[9]
Mineral (geochemical)	Ionic reactions form carbonate minerals (calcite, magnesite etc.)	Centuries → millennia (fast in basalts)	Ultimate permanent fixation when kinetics favourable	[36]

Site Characterization and Selection Criteria

A robust site characterization and rigorous selection process are foundational to safe, effective geological CO₂ storage. Choosing appropriate subsurface targets requires integrated evaluation of geological architecture, reservoir quality, caprock integrity, geomechanical behavior, and proximity to CO₂ sources and infrastructure [36]. Equally important are monitoring capability, regulatory fit, and socio-economic considerations. The following concise notes summarize the principal criteria and the rationale behind them.

Geological and Geomechanical Considerations

Understanding the regional and local geology is the first step in screening potential storage sites. Key features include stratigraphy, structural traps, fault and fracture networks, and the distribution of

Through these models, operators can estimate partitioning among trapping modes, predict pressure evolution, and assess long-term storage security.

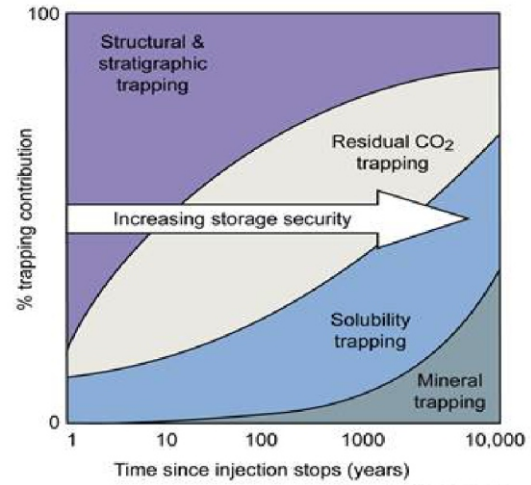


Figure 2. CO₂ trapping mechanisms' performance over time
Source: [21]

In summary, the four principal trapping mechanisms, structural, residual, solubility, and mineral trapping, operate in sequence and synergy to progressively immobilize CO₂. Their relative importance shifts over time: structural and residual trapping are dominant in the early phase, solubility trapping builds in the intermediate stage, and mineral trapping secures permanence over geological durations. The detailed understanding of each mechanism, coupled with predictive modeling, is central to the design, site selection, and risk management of geological carbon sequestration operations.

permeable and impermeable units. Geomechanical analyses assess stress regimes, fault reactivation potential, and the mechanical behavior of caprock and reservoir during injection; this evaluation is essential to minimize risks of induced seismicity and seal failure [37, 38, 39]. High-resolution seismic imaging, well logs, and core data are typically combined to build an integrated geomechanical model that informs injection pressures and rates.

Reservoir Porosity, Permeability, and Caprock Integrity

Reservoirs suitable for CO₂ storage must exhibit adequate effective porosity and permeability to allow injectivity and storage capacity, while caprocks must provide continuous, laterally extensive low-permeability seals [40]. Heterogeneity at multiple scales affects plume migration, residual trapping

efficiency, and dissolution rates; hence, characterization should include petrophysical analysis, relative-permeability measurement, and capillary pressure curves to predict multiphase flow behavior and residual trapping potential.

Depth, Pressure, and Temperature Constraints

CO₂ is typically injected into formations deeper than ~800 m to maintain supercritical conditions that facilitate higher storage density and favorable flow characteristics^{41,42}. Temperature and pressure regimes influence CO₂ phase behavior, solubility in formation waters, and reaction kinetics for mineral trapping. Pressure management is critical: injection must avoid exceeding fracture pressure or inducing transmissivity changes in overlying formations, a concern addressed through pressure-propagation modeling and, where necessary, active pressure mitigation[43,44].

Monitoring and Verification Techniques

A comprehensive monitoring plan is required for regulatory compliance and long-term risk management. Typical monitoring suites combine surface and subsurface methods: time-lapse (4D) seismic and passive seismic monitoring for plume and

induced seismicity; repeat well logging and pressure/temperature sampling for subsurface verification; soil-gas and atmospheric monitoring for near-surface leakage detection; and groundwater sampling for water quality [45, 46]. Advances in remote sensing, distributed fiber-optic sensing, and data analytics (including machine learning) are improving detection limits and enabling real-time anomaly detection.

Case Studies of Successful Site Selection

Field projects illustrate rigorous selection and characterization practice. The Sleipner project (North Sea) selected a high-quality Utsira saline aquifer with a thick, laterally continuous caprock and ample capacity, enabling continuous injection since 1996 with extensive seismic monitoring. The Weyburn-Midale project leveraged a depleted hydrocarbon reservoir with historical production data, known seals, and existing infrastructure, advantages that reduced subsurface uncertainty and project cost[47]. These cases demonstrate the value of combining regional geology, historical reservoir performance, and comprehensive monitoring to ensure operational safety and public confidence.

Table 3. Site-characterization criteria (minimum screening parameters)

Parameter	Screening target / desirable range	Purpose / rationale	References
Depth	> ~800 m	Maintain CO ₂ in supercritical phase for density & injectivity (IPCC guidance)	[27]
Porosity (effective)	Preferably >10% (site dependent)	Storage capacity; pore volume for CO ₂	[4]
Permeability (effective)	Depends on injection strategy; 10s–100s mD desirable for injectivity	Enable practical injection rates; control plume spread	[4]
Caprock integrity	Continuous, laterally extensive low-permeability seal; thickness variable (>10–20 m often preferred)	Prevent upward migration and leakage	[4]
Fault & well inventory	Low density of active leaking wells; mapped faults with assessed sealing behavior Reduce leakage/induced-	Reduce leakage/induced-seismicity pathways	[9]

Risks and Environmental Challenges

While geological carbon sequestration (GCS) presents a viable long-term pathway for mitigating atmospheric CO₂ accumulation, it is accompanied by a range of technical, environmental, and societal risks that must be comprehensively assessed and managed. Understanding these potential challenges is critical to ensuring the safety, permanence, and public acceptance of CO₂ storage projects[8].

CO₂ leakage Pathways and Migration Risks

The foremost concern in GCS is the potential leakage of injected CO₂ through faults, fractures, or wellbores. Leakage risks may arise from incomplete caprock sealing, abandoned wells, or pressure-induced reactivation of geological structures [49, 50]. Although studies suggest that the probability of significant leakage is low if sites are carefully selected and managed, even minor migration could compromise storage integrity or contaminate shallow groundwater systems. Advanced reservoir modeling and long-term surveillance are therefore essential to predict migration behavior and prevent escape to the atmosphere.

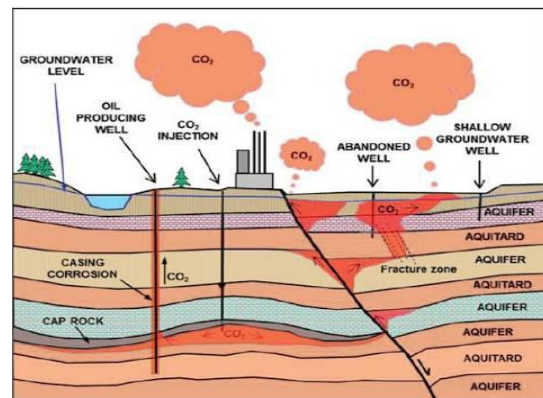


Figure 3. Schematic figure showing potential leakage pathways from a geological CO₂ storage site
Source: [22]

Induced Seismicity and Geomechanical Impacts

CO₂ injection alters subsurface pressure regimes, potentially inducing seismic events if stresses exceed the strength of faults or caprock layers [1, 2, 3]. While most induced events are of low magnitude, their occurrence can undermine public confidence and regulatory approval. Effective management involves geomechanical modeling, real-time microseismic monitoring, and pressure control during injection operations⁴. Recent advances in coupled hydro-mechanical modeling have improved the prediction of fault reactivation and optimized safe injection rates.

Groundwater Contamination and Geochemical Interactions

Leakage of CO₂ into overlying aquifers could acidify groundwater, mobilize heavy metals, or alter mineral equilibria [5]. Geochemical reactions between CO₂, brine, and rock minerals can either enhance storage through mineralization or pose contamination risks depending on mineralogy and fluid chemistry. Laboratory experiments and field observations have shown that, under proper site conditions, mineral trapping can mitigate these effects over time. Hence, site-specific hydrogeochemical assessments are indispensable for understanding potential contamination pathways and long-term water quality impacts.

Long-term Monitoring and Uncertainty Management

Ensuring the permanence of stored CO₂ requires long-term post-injection monitoring and robust risk assessment frameworks.

Table 4. Major risks and representative mitigation measures for GCS projects

Risks	Typical root causes	Representative mitigation approaches	References
Borehole leakage (abandoned/poorly sealed wells)	Legacy wells, poor cementing	Well-integrity surveys, re-cementing, area-of-review, well databases	[9]
Migration via faults/fractures	Natural or reactivated faults, high injection pressure	Geomechanical assessment, conservative pressure management, microseismic monitoring	[34]
Induced seismicity	Pore-pressure increase near critically stressed faults	Real-time seismic monitoring, traffic-light systems, injection rate control	[34]
Groundwater contamination	CO ₂ /brine migration into potable aquifers	Hydrogeochemical baseline, monitoring wells, injection depth and isolation planning	[26]
Social acceptance	Perceived risk, distrust, inadequate consultation	Transparent stakeholder engagement, accessible monitoring data, benefit sharing	[40]

Technological Innovations and Monitoring Tools

Technological innovation is central to the advancement, safety, and scalability of geological carbon sequestration (GCS). Over the past decade, progress in CO₂ injection design, monitoring technologies, and digital tools has significantly improved the precision, efficiency, and transparency of storage operations [8]. Integrating these technologies ensures that CO₂ remains securely contained in geological formations while enabling better prediction, verification, and public confidence in GCS deployment.

Advances in CO₂ Injection and Well Design

Innovative wellbore materials, completion techniques, and pressure control systems have reduced mechanical failures and leakage risks. Modern injection wells employ corrosion-resistant alloys and polymer-lined casings to withstand acidic environments and high pressures. Multi-zone injection and horizontal well configurations allow more efficient plume distribution and enhanced injectivity. Pressure management innovations such as brine extraction and re-injection help mitigate induced seismicity and maintain reservoir stability.

Geophysical and Geochemical Monitoring Technologies

Recent advances in geophysical imaging, particularly time-lapse (4D) seismic surveys, electromagnetic methods, and distributed acoustic sensing have improved plume tracking and caprock integrity assessment [10]. Geochemical monitoring, including isotopic and tracer analyses, provides insight into

fluid-rock interactions and CO₂ dissolution behavior. Combined geophysical-geochemical approaches yield multi-dimensional data that improve confidence in subsurface modeling and verification processes.

Public Perception and Social Acceptance

Beyond technical risks, social and ethical dimensions play a vital role in the deployment of GCS. Public opposition often arises from perceived risks of leakage or induced seismicity, distrust of operators, or inadequate communication. Transparent stakeholder engagement, community consultation, and regulatory oversight are crucial to build trust and foster local acceptance. Education and outreach can demystify the technology and highlight its role in achieving climate goals.

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Remote Sensing and Real-Time Data Analytics

Satellite-based remote sensing using hyperspectral and infrared technologies now enables large-scale atmospheric CO₂ monitoring and early detection of surface leaks. Integration of continuous downhole data streams with cloud-based platforms allows near-real-time visualization of reservoir pressure, temperature, and flow dynamics. Such digital twin systems replicate storage behavior under varying injection conditions, facilitating predictive maintenance and adaptive control [11].

Role of AI and Machine Learning in GCS Monitoring and Prediction

Artificial intelligence (AI) and machine learning (ML) are revolutionizing subsurface monitoring and risk prediction. These models enable automated anomaly detection, plume migration forecasting, and optimization of injection strategies [12]. Deep learning algorithms applied to seismic datasets can distinguish CO₂-saturated zones from background noise with higher accuracy than conventional inversion methods. AI-driven uncertainty quantification frameworks are also enhancing decision-making under complex geological conditions.

Integration with Carbon Capture and Utilization (CCU) Systems

Coupling GCS with carbon capture and utilization technologies creates a more circular and economically viable carbon management framework. Innovations such as CO₂-enhanced geothermal systems and mineralization-based utilization (e.g., carbonate construction materials) bridge the gap between sequestration and industrial value creation [13]. Integrated CCS-CCU infrastructures align with net-zero pathways by maximizing CO₂ use while ensuring safe long-term storage [14].

Collectively, these technological advances underscore a shift toward digitally enhanced, risk-aware, and efficiency-optimized GCS systems. Future progress will likely depend on open data sharing, international technology transfer, and the continued convergence of AI, geoscience, and engineering disciplines to achieve secure and scalable carbon storage.

Table 5. Monitoring and emerging technologies: capability vs limitation

Technology	Main application	Strength	Main limitation	Sources
Time-lapse (4D) seismic	Subsurface plume imaging	High spatial resolution for plume mapping	Costly; offshore logistics	[15]
Distributed fiber-optic sensing (DAS/DTSS)	Continuous downhole temperature/strain/pressure	High temporal resolution; real-time	Coverage limited to instrumented wells; data volumes large	[12]
InSAR / satellite geodesy	Surface deformation detection over large areas	Broad coverage; non-intrusive	Needs calibration; may not detect deep CO ₂ directly	[32]
Machine learning/AI analytics	Anomaly detection, predictive modeling	Improves pattern recognition and forecast speed	Data quality/quantity dependent; interpretability	[35]
Digital twin/integrated risk models	Real-time decision support and scenario testing	Integrates multi-physics, monitoring & operations	High computational & data needs; model validation required	[30]

Economic, Policy, and Regulatory Dimensions

The economic viability of geological carbon sequestration (GCS) is a principal determinant of its scale and pace of deployment. Costs associated with CO₂ capture, transport, injection, monitoring, and long-term liability management can be substantial, frequently posing barriers to adoption in industrial settings [15]. According to a recent study, cost cost-effectiveness of CCS must be assessed relative to the social cost of carbon and competing mitigation options, with transport and site-specific storage costs exerting a large influence. To improve consistency in cost assessment, an IEA/IEAGHG white paper has called for improved guidelines for estimating future “nth-of-a-kind” (NOAK) costs and uncertainty analysis in techno-economic studies [16]. Persistently high costs remain a central challenge: capture units tend to be customized, scale-up is slow, and economies of learning have not been realized to the level seen in renewables, as described in policy analyses.

To overcome these cost barriers, robust policy frameworks and incentive mechanisms are essential. Carbon pricing, tax credits, and emissions trading systems create market demand for CO₂ removal and storage. For example, subsidies or credit schemes like the U.S. 45Q tax credit or EU ETS allowances help bridge the economic gap [17]. Public-private partnerships (PPPs) can also de-risk investment in CCS infrastructure by sharing cost burdens and risk across stakeholders. In many jurisdictions, direct government support is necessary during the early deployment phase to incentivize private investment. The institutional design of such support influences whether CCS becomes a mature, scalable technology or remains niche.

Legal and regulatory regimes underpin the governance of CO₂ storage and must establish clarity around site rights, injection permits, long-term liability, and cross-boundary CO₂ transport. Regulations must delineate responsibilities for post-closure monitoring and remediation, including legal liability residuals, to provide investor certainty. Some regions have adopted “polluter pays” principles, while others assign ownership of stored CO₂ or liability to state or private entities.

Internationally, the London Protocol and amendments addressing subsea CO₂ transport and injection cross national boundaries facilitate transboundary geological storage projects, but implementation remains uneven [18]. International climate agreements, such as the Paris Agreement and IPCC pathways, underscore that deployment of negative emissions technologies, including GCS, must align with global carbon budgets and national emission targets.

Finally, investment opportunities hinge on scalable infrastructure, standardization, and ecosystem coordination. Large-scale CCS often requires networked CO₂ transport pipelines and hub storage sites to reduce unit costs via economies of scale; clustered industrial CO₂ sources may share infrastructure to reduce cost per ton [19]. In emerging markets, leveraging revenues from enhanced oil recovery (EOR) can offset initial costs, although overreliance on fossil fuel incentives must be avoided. Transparent reporting, crediting frameworks, and tracking carbon credits are also fundamental to channeling capital toward GCS projects. Without robust policy, regulatory, and economic instruments, even the technically feasible GCS projects may struggle to scale.

Opportunities and Future Prospects

As pressures mount to meet global climate targets, geological carbon sequestration (GCS) is positioned to play a pivotal role not only in emissions mitigation but also in enabling new synergies across energy, industrial, and environmental systems. One of the most promising routes is coupling GCS with enhanced oil recovery (EOR) and carbon capture, utilization, and storage (CCUS) strategies. CO₂-EOR can serve as an intermediate revenue stream while achieving permanent storage of injected CO₂ [20]. When properly managed, lifecycle assessments suggest that many EOR operations can yield net negative CO₂ outcomes over significant portions of their operational lifetimes. This linkage reduces the upfront financial burden of pure storage projects by leveraging existing oil infrastructure and can accelerate broader CCS deployment in the near term [21].

Another major opportunity lies in aligning GCS with hydrogen and other negative-emissions technologies. The integration of CCS with hydrogen production especially from fossil-based or biomass feedstocks, presents a pathway to decarbonize hard-to-abate industries [22]. Indeed, recent analyses highlight that hydrogen supply chains incorporating capture, transport, and storage infrastructure become more resilient and cost-effective when CO₂ sinks are co-developed [23]. Similarly, technologies like bioenergy with CCS (BECCS) and direct air capture (DAC) can complement GCS by providing net-negative CO₂ removal when storage capacity and monitoring protocols are robust. Thus, GCS has the potential not only to reduce emissions but to serve as a backbone for negative emissions in ambitious climate pathways [24].

Emerging research directions further broaden the opportunity space. For example, the development of digital twins and AI-driven simulation frameworks can drastically reduce uncertainty and enhance real-time control of CO₂ subsurface behavior. Physics-informed machine learning models promise to bridge gaps between high-fidelity simulation and operational speed, thus improving predictive performance and risk management [25]. Advances in mineralization pathways, especially in basalt and ultramafic rock formations, offer the opportunity for faster geochemical fixation of CO₂, enhancing permanence beyond conventional solubility trapping. Moreover, clustered carbon transport and storage hubs, analogous to industrial “CO₂ hubs,” present a scalable infrastructure model that spreads fixed costs, improves utilization of storage sites, and encourages economies of scale.

For GCS to realize these opportunities, strategic coordination among stakeholders is essential. Policymakers must design incentives, carbon pricing, and regulatory frameworks that support cross-sector integration. Research institutions and industry should commit to open data, standardized protocols, and interoperable modeling frameworks. International collaboration can facilitate technology transfer, joint deployment of hubs, and harmonization of liability and monitoring standards across borders. In sum, the future direction for GCS is one of convergence: merging technological innovation, system integration, and policy alignment to elevate GCS from niche projects to central enablers of a net-zero energy future [26].

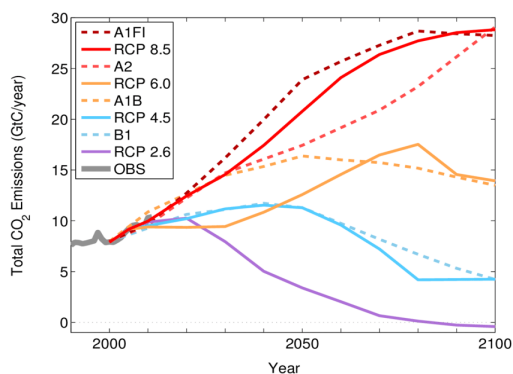


Figure 4. Future greenhouse gas scenarios range from aggressive reductions to large increases in greenhouse gas emissions
Source: [37]

Challenges and Knowledge Gaps

Despite the steady progress in demonstration projects and modeling capabilities, geological carbon sequestration (GCS) continues to face persistent knowledge and implementation gaps that constrain large-scale, long-term deployment. Key uncertainties lie in the characterization of subsurface heterogeneity, the predictability of multiphase flow and geochemical reactions, and the verification of long-term storage security. These challenges intersect with issues of public perception, liability management, and integration into broader decarbonization strategies [27].

Technical Uncertainties and Data Limitations

A central limitation of GCS lies in the incomplete understanding of geological variability and reservoir dynamics. Storage efficiency and capacity estimates are strongly affected by assumptions regarding porosity, permeability, and caprock integrity, which differ markedly across sedimentary basins [28]. Moreover, legacy wells and faults introduce additional leakage pathways that are difficult to quantify. Advanced numerical simulations such as ensemble and Monte Carlo models, have improved predictive reliability but remain dependent on limited field data and site-specific calibration. Consequently, reducing data uncertainty through extensive core sampling, well logging, and tracer studies remains vital for credible capacity estimation and risk assessment [29].

Long-Term Storage Validation, Monitoring, and Liability Concerns

Ensuring the permanence of stored CO₂ over centuries is one of the greatest scientific and policy challenges. Monitoring periods rarely exceed a few decades, making extrapolation over millennial timescales inherently uncertain [30]. Integrated frameworks such as the U.S. National Risk Assessment Partnership (NRAP) provide probabilistic models to predict leakage and pressure build-up, but these rely on simplifying assumptions that require continuous field validation. Beyond technical aspects, liability for post-closure storage remains a pressing issue. Jurisdictions differ on when and how liability transfers from operators to the state, highlighting the need for long-term stewardship frameworks and financial assurance mechanisms.

Integration with renewables and energy-system interactions

GCS deployment must align with broader low-carbon energy transitions. Its feasibility depends on capture supply chains, CO₂ transport networks, and compatibility with renewable-based systems³¹. Studies suggest that uncoordinated CCS expansion could risk locking in fossil-fuel infrastructure rather than facilitating decarbonization³². Therefore, systems-level integration, where GCS complements renewable power and negative-emission technologies, will be crucial to achieving cost-effective and sustainable net-zero pathways.

Need for Multidisciplinary Research

Collaboration

Addressing these uncertainties requires integrated research across disciplines. Collaboration between reservoir engineers, geochemists, economists, and social scientists allows for holistic assessments that couple technical risk modeling with socioeconomic and governance factors. Shared data platforms, open-access testbeds, and standardized monitoring protocols enhance collective learning and reduce redundancy. Such multi-actor engagement is also instrumental for adaptive management frameworks that combine predictive modeling with real-time monitoring feedback [33].

Addressing Social and Ethical Implications

Public perception remains a decisive factor in GCS project success. Negative community attitudes, often rooted in perceived safety risks or mistrust in institutions, have led to the suspension of several pilot projects [34]. Transparent communication, participatory site selection, and demonstrable monitoring performance are therefore essential to build social license to operate. Ethical dimensions, including intergenerational stewardship, equity in risk distribution, and accountability for long-term management, are equally vital to secure enduring public and political support.

Conclusions

Geological carbon sequestration (GCS) stands as a crucial component of global strategies for mitigating climate change by securely storing CO₂ in deep geological formations. Significant progress has been made in understanding storage mechanisms and improving monitoring technologies, which enhances confidence in long-term storage integrity. However, challenges such as subsurface uncertainty, leakage risks, and public skepticism remain barriers to large-scale deployment. Addressing these issues requires technological innovation, transparent governance, and supportive policy frameworks that encourage investment and cross-sector collaboration. In essence, the future of GCS depends on sustained research, digital monitoring advances, and international policy coordination. If effectively integrated into broader decarbonization strategies, GCS can play a vital role in achieving global net-zero emission goals.

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Conflict of Interest

The authors declared that there are no conflicts of interest.

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