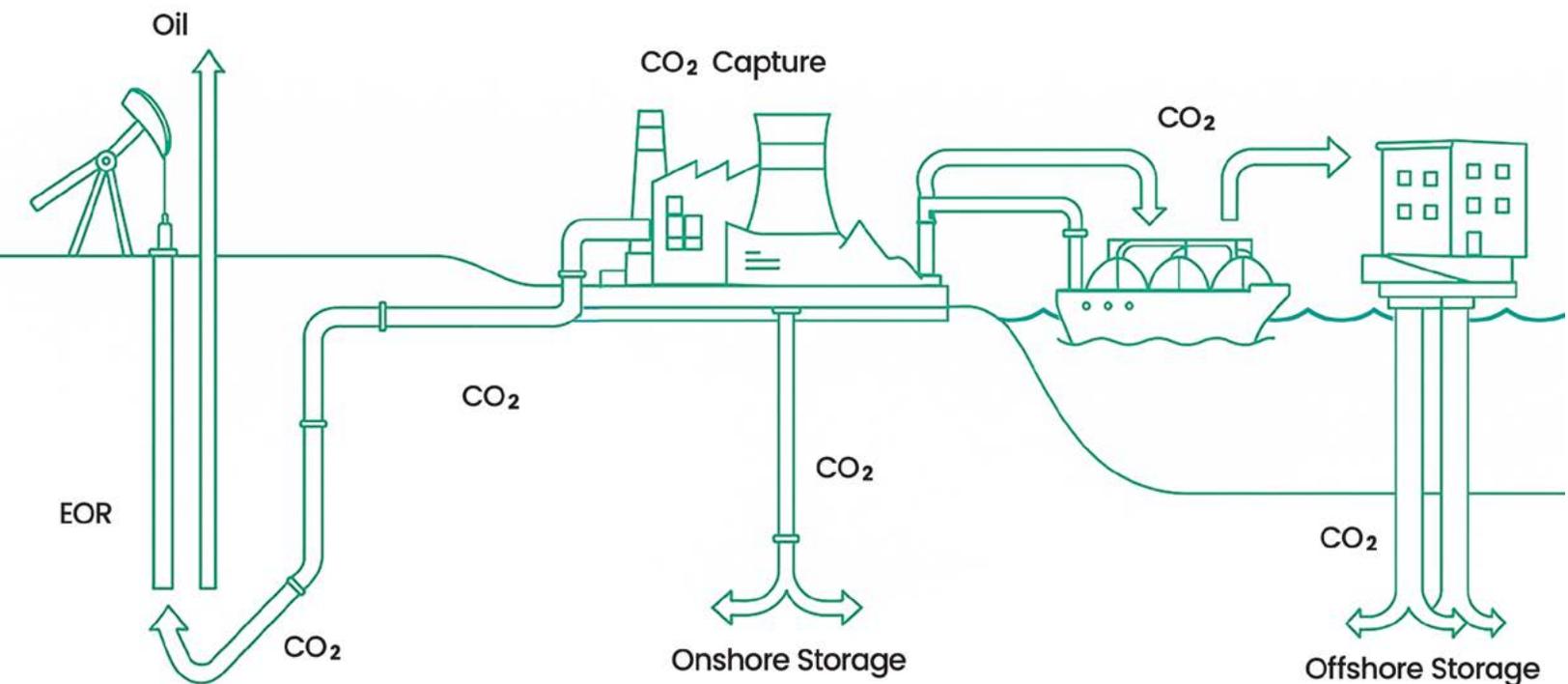




The Science of Safe Carbon Storage



Your CCS Learning Journey

This is Part 1 of a three-part series on Carbon Capture and Storage (CCS). In this edition, you'll explore the science of safe storage—how CO₂ behaves underground, the mechanisms that trap it, and the formations best suited for permanent security.

Next, continue your journey with:

Part 2 – De-risking CCS Projects: Risks, regulations, site selection, and compliance.

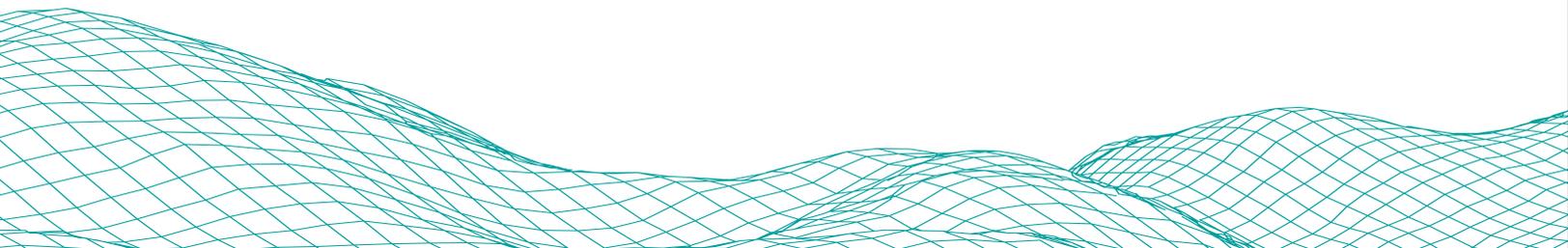
Part 3 – Making CCS Work: Economics, optimization strategies, and CMG's CCS solutions.

Together, these three volumes provide a complete foundation—from the science to the strategies – for building successful CCS projects.

What You Will Learn

Introduction: The Importance of Scientific Principles

- 1. How CO₂ gets locked underground**
- 2. Why CO₂ behaves differently underground**
- 3. Where CO₂ can be stored**
- 4. The foundation of safe storage**
- 5. From science to practice**



Introduction: The Importance of Scientific Principles

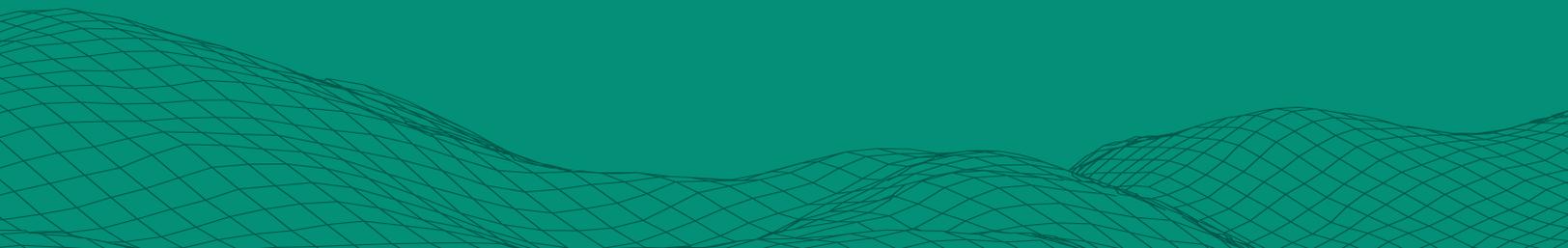
Carbon Capture and Storage (CCS) stands as one of the most effective tools for addressing greenhouse gas emissions. The science of geological storage is grounded in decades of reservoir engineering and geoscience. At depths greater than 800 meters, CO₂ enters a supercritical state, combining the density of a liquid with the mobility of a gas. This physical state allows efficient injection and shapes how the plume moves underground.

Long-term containment relies not on a single barrier but on a portfolio of complementary mechanisms. Structural barriers, pore-scale trapping, solubility in brine, and mineralization all work together across different timescales. Their combined effect, reinforced by the physical properties of CO₂ and the formations selected for storage, ensures permanence.

This ebook explores the science of safe carbon storage. We begin with the mechanisms that trap CO₂ underground, examine its physical behavior at storage depths, and review the geological formations best suited to secure it for millennia.



1. How CO₂ gets locked underground



The effectiveness of geological storage comes from four primary trapping mechanisms. Each operates on different timescales and under different conditions, creating layers of security that overlap and reinforce one another.

Structural and stratigraphic trapping: sealing CO₂ with rock layers

When CO₂ is injected, buoyancy drives it upward until it is contained by impermeable formations.

- **Structural traps** form when CO₂ accumulates beneath a caprock such as shale or salt within domes, anticlines, or fault-bounded closures.

- **Stratigraphic traps** occur when changes in rock type, such as sandstones pinching out against impermeable shales, create natural seals.

These mechanisms provide the first line of containment in the early decades of a project.

Their success depends on:

- Caprock integrity and fracture resistance.
- Reservoir geometry.
- The density contrast between CO₂ and brine.
- Careful management of injection pressures.

Structural and stratigraphic trapping offer proven containment, similar to how hydrocarbons have been stored naturally for millions of years. Their main limitations are their dependence on seal integrity and the risk of compromised faults or old wells.



Residual trapping: locking CO₂ in the pore space

As CO₂ migrates through a reservoir, part of it becomes immobilized in pore spaces. Once the plume passes, brine flows back in, and capillary forces break the gas into isolated bubbles that remain trapped.

This process is effective almost immediately and continues for decades, offering a robust layer of security. Its efficiency depends on rock wettability, pore geometry, interfacial tension, and saturation levels.

Advantages:

- Immobilizes CO₂ regardless of caprock integrity.
- Reduces plume migration distance.

Limitations:

- Hard to measure at field scale because of geological variability.

Dissolution trapping: dissolving CO₂ into brine

CO₂ can dissolve into formation water, forming a denser brine that may sink and drive further mixing. Once dissolved, it no longer exists as a buoyant phase.

This mechanism develops over hundreds to thousands of years and is influenced by pressure, temperature, salinity, porosity, and convection currents.

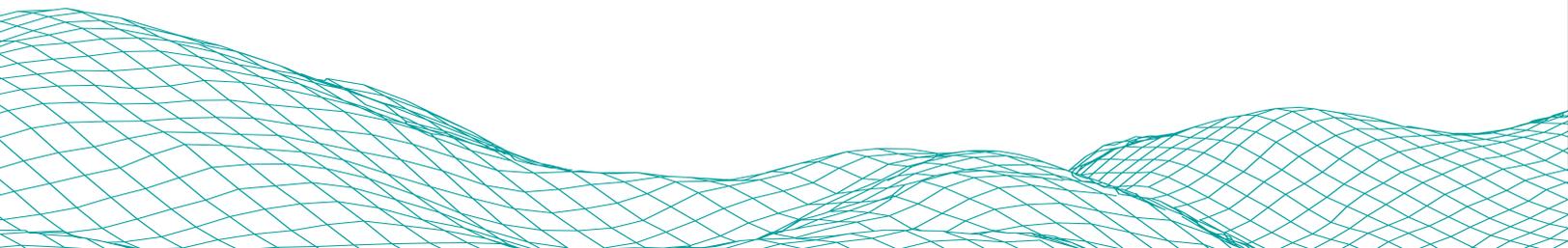
Advantages: Provides long-term security by eliminating mobile CO₂.

Limitations: Dissolution is slow, and effectiveness is reduced in hot or saline reservoirs.

Mineral trapping: transforming CO₂ into rock

Over even longer timescales, CO₂ dissolved in brine reacts with reservoir minerals to form solid carbonates such as calcite, dolomite, and siderite. Once mineralized, the CO₂ is permanently immobilized.

The rate depends heavily on mineralogy and formation type. In sandstones, significant mineral trapping may take tens of thousands of years. In contrast, basalts rich in reactive silicates can achieve rapid mineralization in just a few years, as demonstrated in field projects such as [CarbFix in Iceland](#).



Advantages: The most secure and permanent form of storage.

Limitations: Reaction rates are slow in most sedimentary rocks and can be difficult to predict.

These combined mechanisms create a secure, multi-layered system, guaranteeing the safe and permanent subsurface storage of CO₂.

Comparative Overview of CO₂ Trapping Mechanisms

Comparing the four mechanisms

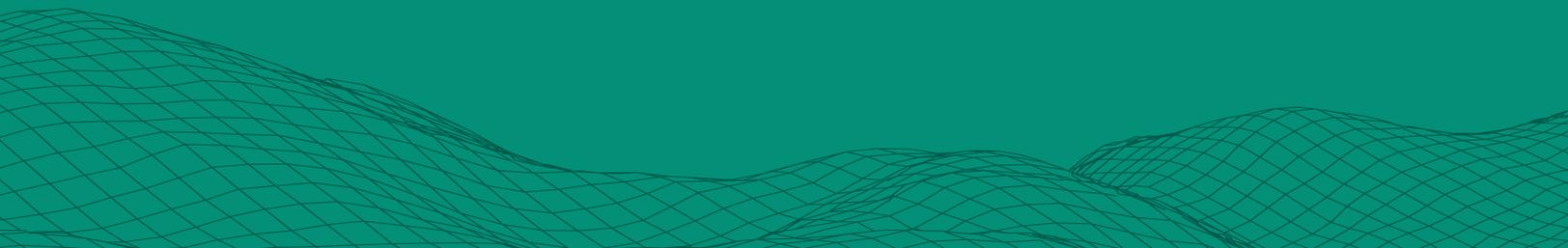
- **Structural/stratigraphic trapping:** Immediate containment, dependent on seal integrity.
- **Residual trapping:** Effective within decades, independent of caprock.
- **Dissolution trapping:** Medium-term mechanism, slow but reliable.
- **Mineral trapping:** Ultimate permanence, effective over millennia.

A clear understanding of the different trapping mechanisms is essential for evaluating the security, efficiency, and long-term performance of geological CO₂ storage. The following table summarizes the main features, advantages, and limitations of each trapping mechanism.

Mechanism	Timescale	Main Advantage	Key Limitation
Structural/Stratigraphic	Immediate to long-term	Provides primary containment of CO ₂ plume	Depends on caprock integrity
Residual (Capillary)	Years to decades	Immobilizes CO ₂ quickly in pore spaces	Hard to quantify at field scale
Dissolution	Decades to centuries	CO ₂ becomes part of formation water	Slow process; reduced at high salinity
Mineralization	Centuries to millennia	Permanent conversion to stable minerals	Very slow in most sedimentary rocks



2. Why CO₂ behaves differently underground



In its supercritical state, CO₂ combines liquid-like density with gas-like viscosity.

This balance is what makes geological sequestration possible. At depths greater than 800 meters, density stabilizes between 500 and 800 kg/m³, while viscosity remains an order of magnitude lower than water. The result is efficient injectivity and the ability to maximize storage space.

Compressibility plays an important role near the critical point. Small pressure changes can drive large shifts in density, which in turn influence plume migration and buoyancy. In saline aquifers, the density contrast between CO₂ and brine creates strong upward migration forces. In oil reservoirs, miscibility effects moderate

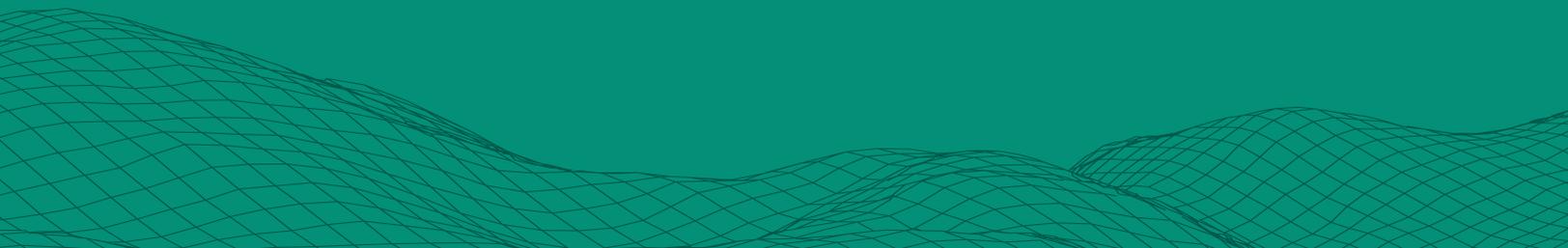
this behavior, while in gas reservoirs, CO₂ can actually migrate downward, since it is denser than methane.

Salinity further complicates this picture. As brine salinity increases, solubility decreases, sometimes by nearly an order of magnitude. While this reduces the effectiveness of dissolution trapping, density and viscosity remain the dominant factors in long-term storage performance.

These thermophysical properties collectively dictate the movement and trapping of injected CO₂, as well as the security of storage over geological timescales.



3. Where CO₂ can be stored



Geological formations offer a diverse set of options for secure storage. Each has unique advantages, challenges, and proven examples from the field.

Depleted oil and gas reservoirs

These reservoirs have already held hydrocarbons for millions of years, making them natural candidates for CO₂ storage. Their proven containment and existing infrastructure reduce uncertainty and cost.

- **Capacity:** Estimated at 675–900 Gt globally.
- **Advantages:** Proven seal integrity, abundant data from exploration, existing wells and pipelines.
- **Challenges:** Legacy well integrity and limited availability.
- **Example:** The Weyburn-Midale project in Canada has stored nearly 40 Mt of CO₂ while enhancing oil recovery, demonstrating both storage security and economic viability.

Deep saline aquifers

The largest potential storage resource lies in deep saline formations. They are widely distributed, often close to major emission sources, and benefit from multiple trapping mechanisms working together.

Global capacity estimates range from 8,000 to 55,000 Gt, though uncertainty remains due to limited characterization. Projects like Sleipner (Norway, operating since 1996), Snøhvit (Norway), Quest (Canada), and Gorgon (Australia) show that aquifers can handle millions of tonnes of injection safely.

The main drawback is that aquifers have little historical data compared to oil and gas fields, making early characterization critical.



Enhanced oil recovery (EOR)

CO₂ injection for enhanced oil recovery extends field life while providing storage. A fraction of injected CO₂ remains in place, creating a dual benefit.

- **Global capacity:** 61–123 Gt CO₂.
- **Advantages:** Offsets storage costs through oil production, mature and proven technology.
- **Challenges:** Balancing economic recovery with long-term retention, complex accounting frameworks.
- **Example:** The Permian Basin in Texas injects ~30 Mt CO₂ annually across 50+ projects, making it one of the largest demonstrations of CO₂ injection worldwide.

Coalbeds (Enhanced Coalbed Methane – ECBM)

Coal seams adsorb CO₂ onto organic matter while releasing methane, providing both storage and a potential revenue stream.

- **Global capacity:** 60–200 Gt CO₂ (though practical capacity is much lower).
- **Advantages:** Secure adsorption trapping, economic offset from methane production.
- **Challenges:** Narrow depth window, injectivity loss due to coal swelling, and limited field experience.

Pilot projects in Canada and the U.S. have shown feasibility but remain small in scale.



Basalt formations

Basalts are highly reactive, allowing injected CO₂ to mineralize rapidly into stable carbonates. Unlike sedimentary reservoirs, storage here depends on geochemistry more than pore space.

- **Advantages:** Rapid mineral trapping (years rather than millennia).
- **Challenges:** Low porosity and permeability, reliance on fractures, and scalability still uncertain.
- **Example:** At CarbFix in Iceland, more than 95% of injected CO₂ mineralized within two years, proving the speed of basalt mineralization.

Organic-rich shales

Best known as hydrocarbon source rocks, shales can also adsorb CO₂ on organic matter. Their laminated structure and low permeability enhance seal integrity.

While capacity remains uncertain, the adsorption behavior is comparable to coalbeds.

The main challenge is extremely low injectivity, which limits large-scale deployment.

Salt caverns

Man-made caverns in salt domes provide engineered containment with excellent sealing properties. They offer high injectivity but low total capacity compared to other options.

Their role is most likely as short-term or buffer storage, rather than primary sequestration.

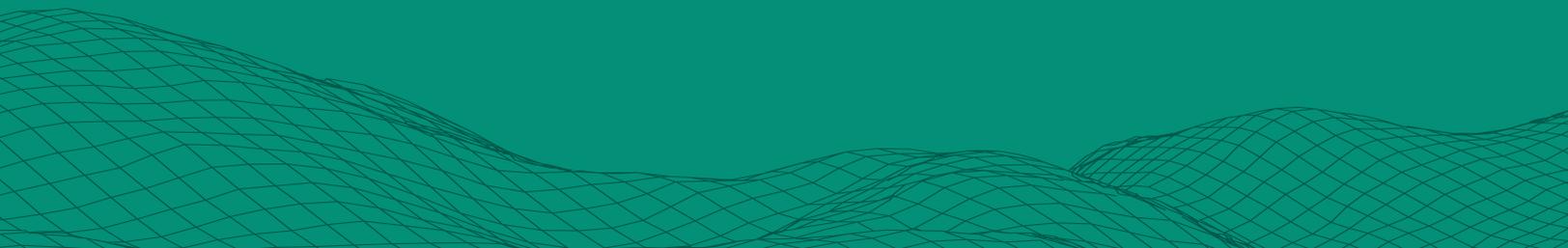
CO₂ hydrates

In [permafrost](#) and deep marine sediments, CO₂ can form crystalline hydrates under high pressure and low temperature. These solid structures may provide stable immobilization, though no large-scale projects exist.

The main challenge is energy intensity and uncertainty around long-term stability. For now, hydrates remain a theoretical option rather than a practical one.



4. The value of multiple options



Each storage pathway brings different strengths. Saline aquifers represent the largest scalable option, depleted reservoirs offer proven integrity, and basalts demonstrate rapid mineralization potential. Others – like coalbeds, shales, salt caverns, and hydrates – expand the portfolio but face technical and economic hurdles.

These combined options facilitate the global deployment of CCS across varied geologies, bolstered by interconnected trapping mechanisms that ensure strong, long-term security.

The science of safe carbon storage is built on overlapping mechanisms and reinforced by the physical properties of CO₂ in the subsurface. Structural and stratigraphic traps provide the first line of defense, residual trapping immobilizes CO₂ within pore spaces, dissolution integrates it into formation waters, and

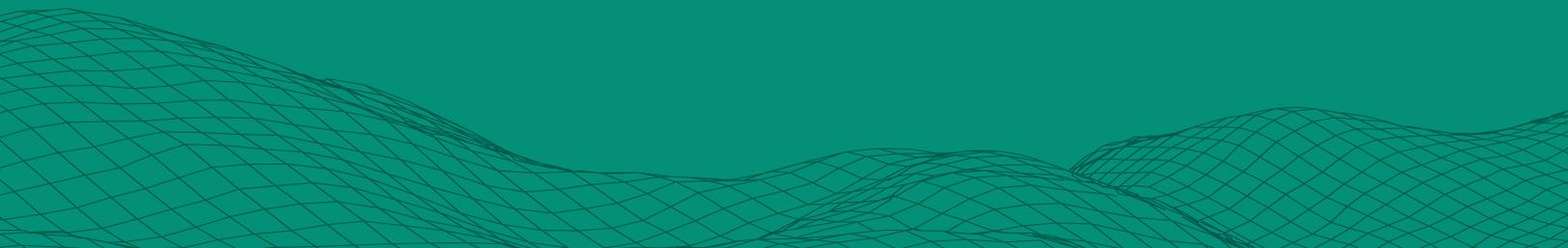
mineralization transforms it into rock. Together, these processes ensure multiple barriers to movement, each reinforcing the others across different timescales.

The choice of storage site plays an equally important role. From depleted hydrocarbon reservoirs to deep saline aquifers, basalts, coalbeds, and even engineered caverns, each geological option offers distinct advantages. Some are proven at scale, others are emerging, but all contribute to a diverse portfolio of pathways that make permanent storage achievable.

Scientific understanding has advanced to the point where these processes can be described, modeled, and validated. Field projects – from Sleipner in the North Sea to CarbFix in Iceland and Weyburn in Canada – demonstrate that storage can be secured for decades to millennia. The physics, chemistry, and geology of CO₂ storage are no longer speculative; they are documented, field-tested, and scalable.



5. From science to practice



Understanding the science is only the first step. To move CCS projects from theory to practice, operators must also navigate risks, regulations, and site-specific challenges.

Geological integrity, geomechanical behavior, and wellbore stability all play a role in long-term security. Selecting the right site and monitoring its performance requires careful planning and compliance with evolving regulatory frameworks.



Learn more about how to de-risk your CCS project at

cmgl.ca/solutions/software/ccs/

 [/computer-modelling-group-ltd/](https://www.linkedin.com/company/computer-modelling-group-ltd/)

 [/compmodgr](https://www.youtube.com/channel/UC...)

 www.cmgl.ca

CMG

Published by Computer Modelling Group Ltd.

© Copyright 2025 Computer Modelling Group Ltd.