GLOBAL CCS INSTITUTE

PERSPECTIVE

THE SAFETY AND PERMANENCE OF CO_2 GEOLOGICAL STORAGE

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1.0 A HISTORY OF SAFE AND EFFECTIVE CO_2 STORAGE

Safe and permanent CO_2 storage is a critical pillar in the fight against climate change, offering a scalable solution to achieve net zero emissions. This perspective examines the history and current state of play, confirming that CO_2 can be stored safely and permanently at the scale required for CCS to deliver deep emission reductions for industry.

Decades of research, development, and deployment (RD&D) have established a robust scientific foundation for CO_2 storage, demonstrating that it is safe and permanent. Academic research, pilot projects, and large-scale demonstration initiatives have bolstered our understanding of CO_2 storage processes. Research has been ongoing since the 1970s, validating and testing the ability of CO_2 to be stored permanently and safely.

Today, we have 18 commercial dedicated[1] CO_2 storage projects (there are also 33 enhanced oil recovery or EOR projects that monitor CO_2 injection and storage, but these are not included in this number) and over 50 pilot and demonstration projects actively injecting and monitoring CO_2. Researchers and industry professionals design these projects to confirm that CO_2 can be effectively injected, stored safely and monitored to confirm permanence.

[1] Dedicated CO_2 storage projects only, where the commercial driver and primary purpose is to store CO_2. Excludes all projects not directly related to CO_2 storage, EOR projects and those not specified. Current as of June 2025.

RESEARCH AND DEVELOPMENT

1970 TO 1980 — INITIAL ACADEMIC STUDIES

CO_2 Storage research begins. Marchetti (1976) identifies storing CO_2 to mitigate the rising CO_2 level, and Horn & Steinberg (1982) publish potential storage sites in the US.

1990s — GLOBAL STORAGE DEVELOPMENT

Norway, Netherlands, UK, Canada, Japan, US and Australia publish first studies on CO_2 storage characterisation. IEAGHG created.

2000s — INTERNATIONAL RECOGNITION

IPCC publishes special report on CCS. UNFCCC recognises CCS in the first assessment report. CSLF[3] and RCSP[4] founded.

NOW — PROLIFERATION OF KNOWLEDGE

70,000 peer-reviewed articles apply scientific methods of observe, test, question, reproduce and openness on CO_2 storage, confirming safety and permanence.

PILOT AND DEMONSTRATION

2001 — WEYBURN – MIDALE (CAN)

Canadian IEAGHG programme tests the safety and permanence of CO_2 used in an enhanced oil recovery field.

2000s — PROOF-OF-CONCEPT PILOTS

Nagaoka (JPN), Otway (AUS), Ketzin (GER), Frio (US), Lacq (FRA), advancing characterisation, injection, and CO_2-specific monitoring technology. Nagaoka (JPN) pilot injection and monitoring confirms safety and permanence during earthquake.

2010 TO 2020 — DEMONSTRATING STORAGE

Shenhua Ordos (CHN), Illinois Decatur (US), Tomakomai (JPN), demonstrates CO_2 storage and monitoring at commercial scale. CarbonSAFE hosts 24 validation and testing projects.

NOW — 50 PILOTS AND DEMONSTRATION

Globally, 50 pilot and demonstration projects, confirming the safe and permanent storage of CO_2.

COMMERCIAL REALITY

1996 — SLEIPNER (NOR)

Start of the Sleipner project (NOR) — first commercial-scale saline formation storage. Sleipner has now been operating for 30 years, storing around 20 million tonnes[2] of CO_2.

2000 TO 2020 — COMMERCIAL-SCALE SUCCESS

Quest (CAN), In Salah (ALG), Boundary Dam (CAN), Gorgon (AUS), Illinois Industrial (US), Snøhvit (NOR), Qatar LNG (QAT).

2025 — NORTHERN LIGHTS

A transport and storage network in the offshore Norwegian North Sea stores Europe's emissions from various sources.

NOW — 18 PROJECTS

Operating dedicated geological storage projects globally, storing over 80 million tonnes of CO_2. This excludes EOR projects worldwide.

[2] https://www.equinor.com/news/20240404-reducing-emissions-from-sleipner-and-gudrun
[3] Carbon Sequestration Leadership Forum (CSLF)
[4] Regional Carbon Sequestration Program (RCSP) US

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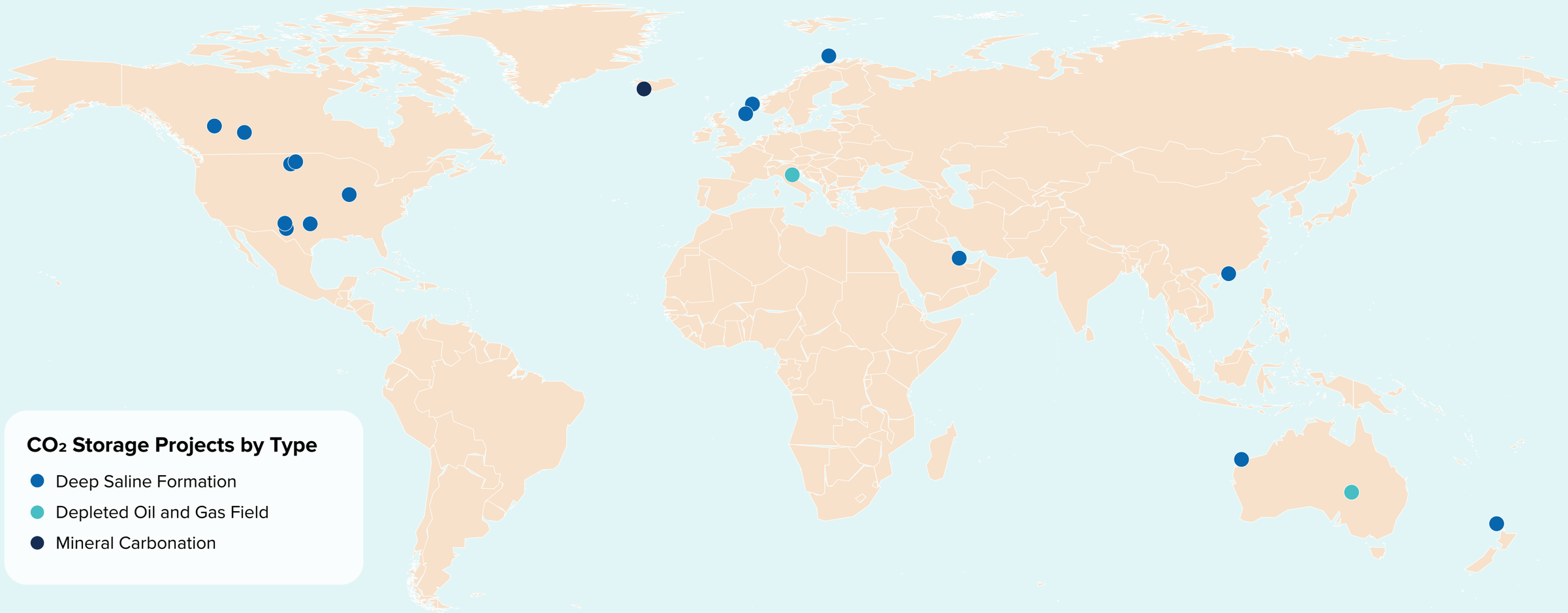
Figure 1: Global operational commercial geological CO_2 storage projects



CCS is a globally recognised tool for permanently reducing and removing CO_2 emissions, starting with Equinor's Sleipner CCS project in 1996. Thirty years later, 18 commercial dedicated geological CO_2 storage projects are currently operational globally, storing over 80 million tonnes of CO_2, demonstrating the safety, reliability, and scalability of CO_2 storage globally[5]. These commercial projects are spread around the world, with most located in the US (6), but extending across Canada (2), Iceland (1), Norway (3), Italy (1), Qatar (1), China (1), Australia (2) and New Zealand (1).

Five of these projects are offshore, while the remaining ones operate onshore, showcasing the flexibility of CO_2 storage technologies to adapt to both marine and terrestrial environments. The Snøhvit Project, located in the Barents Sea within the Arctic Circle, exemplifies offshore storage in extreme cold, having operated safely since 2008. On the other hand, the Moomba project in the arid Australian desert injects 1.7 million tonnes of CO_2 annually, proving the feasibility of storage in harsh, remote regions. The global distribution of these projects highlights the adaptability of CO_2 storage to diverse locations, geological settings, and depths, and demonstrates its feasibility regardless of geographic or environmental challenges.

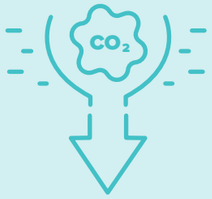
Over three decades of operational experience with CO_2 storage projects have provided invaluable insights into ensuring safe and permanent storage of CO_2. Across the 18 large-scale operational projects to date, there have been no reported cases of CO_2 leakage to the surface causing environmental harm, reinforcing the safety of well-managed geological storage.

[5] Seyyedi, M., Consoli, C., Minervini, J., Hatta, A., & Williams, E. (2024). The Global Landscape of CO_2 Storage Projects: Insights, Trends, and Urgent Action. https://ssrn.com/abstract=5063681

REGULATORY FRAMEWORKS AND STANDARDS GUIDE SAFE CO_2 STORAGE

Regulatory frameworks provide a structured approach to risk management, operational oversight, and long-term monitoring, which are essential for achieving safe and permanent CO_2 containment. Legal and regulatory frameworks have an important role in different storage sites' lifecycles:

Figure 2: The role of legal and regulatory frameworks in the CO_2 storage lifecycle.

SITE SCREENING AND SELECTION	INJECTION OPERATION	CLOSURE AND POST CLOSURE
		
IDENTIFICATION AND SELECTION OF STORAGE SITES	**OPERATION AND STORAGE ACTIVITIES**	**LONG-TERM STEWARDSHIP**
Establishing minimum criteria for geological site suitability, ie, containment properties and minimal risk of leakage. Mandating comprehensive risk assessments throughout the project lifecycle.	Ensuring that best practices are followed, including proper well design, injection rate limits, and pressure management. Requiring continuous monitoring to detect and address anomalies, such as leakage or unintended CO_2 migration, at the earliest stage.	Defining the rules that specify the duration and scope of post-closure monitoring, financial responsibility for maintenance, Defining mechanisms for transitioning liability to a governing authority once the site is secure.

The storage operator will be guided by regulations in all jurisdictions where CCS is employed. In addition to regulations, several guidelines and standards are available, such as the IEAGHG Report[6], the US DOE Best Practice Manuals[7] and the International Standards Organization's ISO 27914:2017 Geological Storage[8], amongst several other standards for ensuring safety and cross-cutting issues. These regulations, standards, and guidelines collectively cover the full range of a CO_2 storage operation, from site selection and characterisation, appraisal, and operation through to post-closure.

[6] IEAGHG. (2009). CCS Site Characterisation Criteria Report 2009/10.

[7] National Energy Technology Laboratory. (2024). Carbon Capture and Storage Best Practice Manuals. https://Netl.Doe.Gov/Carbon-Management/Carbon-Storage/Strategic-Program-Support/Best-Practices-Manuals

[8] International Organization for Standardization. (2016). ISO 27914:2017: Carbon dioxide capture, transportation and geological storage — Geological storage.

CO_2 STORAGE IS PROVEN, SAFE AND PERMANENT

Decades of research, operational advancements, and collaborative efforts have confirmed the safety and permanence of CO_2 storage for CCS operations. Real-world commercial-scale projects, such as Sleipner in Norway, have demonstrated the feasibility, safety, and reliability of CO_2 storage, setting benchmarks for the industry. Active operations worldwide show the adaptability of CO_2 storage to various locations and geological settings. These achievements are complemented by robust regulatory frameworks that ensure the integrity of storage operations, addressing environmental and public safety concerns.

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