Lessons learned from active CO2 injection sites (from large-scale EOR projects to pilots)

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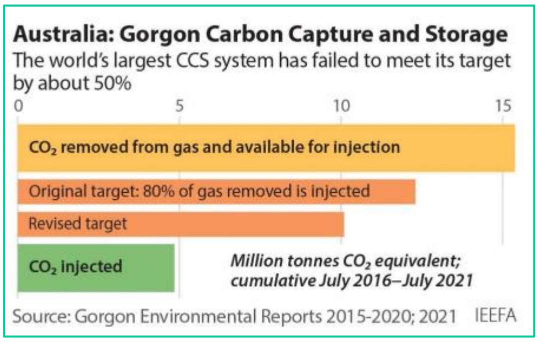
Introduction

Active CO2 injection sites, spanning from large-scale Enhanced Oil Recovery (EOR) projects to smaller-scale pilots, provide invaluable insights into the practical challenges and successes of carbon dioxide (CO2) storage initiatives. This abstract synthesizes lessons learned from these diverse sites, focusing on technical, operational, and regulatory aspects crucial for successful CO2 injection and long-term storage. Key themes include site selection criteria emphasizing geological suitability, the importance of robust monitoring and verification protocols to ensure secure storage, and effective public engagement strategies to garner local support. Additionally, regulatory frameworks and legal considerations are explored, highlighting the necessity of clear guidelines for navigating permitting, liability, and compliance issues. By synthesizing experiences from active CO2 injection sites, this abstract informs future CCS (Carbon Capture and Storage) projects, fostering improved implementation strategies and advancing global efforts towards carbon neutrality and climate change mitigation.

Challenges and lesson learnt.

1. Gorgon project

The Gorgon Carbon Capture and Storage (CCS) project encountered several challenges during its operation. Despite being owned by major companies like Shell, ExxonMobil, and Chevron, Gorgon faced the following difficulties:



Source: Gorgon Environmental Reports 2015-2020; 2021

Figure 1: Gorgon Project

- Underperformance: Gorgon failed to meet its targets for the first five years, underperforming by approximately 50%1. This highlights the technical risks inherent in CCS projects.
- Unique Engineering Challenges: Most CCS projects globally have faced unique engineering challenges, leading to inefficiencies and cost overruns. Gorgon's frequent inefficiencies are typical of these technical risks.

- Carbon Offset Costs: To offset its carbon dioxide (CO2) target shortfall, Gorgon recently acquired and surrendered greenhouse gas offsets recognized by the West Australian Government. Estimates suggest this could cost anywhere from US$100 million to US$184 million1.
- Long-Term Liability: After its expected 40-45 year operational period, there will be a 15-year closure phase. Australian taxpayers are liable for the project during this post-closure period1.
- In summary, Gorgon's experience underscores the complexities and uncertainties associated with CCS technology, even for well-established projects.

The Gorgon Carbon Capture and Storage (CCS) project provides valuable insights into the challenges and successes of CCS technology. Here are some key lessons learned from the Gorgon project:

- Impure Carbon Dioxide Behavior: Over the past five years, our understanding of the thermodynamic and chemical behavior of impure carbon dioxide has significantly improved. This knowledge is crucial for successful CCS implementation.
- Benefit of Hindsight: The Gorgon project has allowed us to reflect on what went well and what could have been done differently. Hindsight informs future CCS projects, helping them avoid pitfalls.
- Learning by Doing: CCS technology is relatively new, and everyone involved is in the "learning by doing" stage. Projects like Gorgon contribute to this collective learning process.

2. In Salah Project

The In Salah CO2 Storage project has been a highly informative demonstration project and the data gathered has been extensively studied and reported in the scientific literature. However, some important general lessons learned can be drawn from this project, as follows:

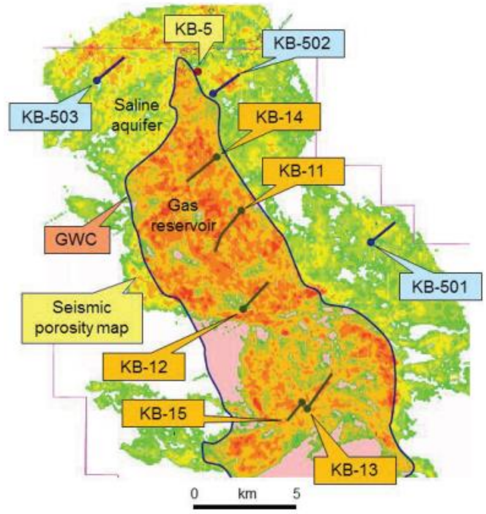


Figure 2: Field layout – In Salah gas development

- Monitoring must be incorporated into the Field Development Plan (FDP) and regular field operations.
- The array of monitoring technologies used at CO2 storage sites primarily includes conventional oilfield methods and practices, supplemented by surface monitoring techniques adapted from standard geotechnical and environmental monitoring practices.
- Satellite InSAR data has proven particularly beneficial for comprehending the geomechanical effects of CO2 injection, but it should be integrated with high-quality reservoir and overburden data and models for comprehensive analysis.
- The monitoring program for storage should be designed to address specific leakage risks identified during the site selection phase and should be adaptable during operations.
- Preserving the integrity of legacy wellbores is crucial for managing leakage risks effectively.
- Gathering, modeling, and integrating a comprehensive set of baseline data, including information on the overburden, is essential for assessing the long-term integrity of storage.
- CO2 plume development exhibits non-uniform characteristics and necessitates high-resolution data for reservoir characterization and modeling.
- Strategies for injection rates and pressures should be closely tied to detailed geomechanical models of both the reservoir and overburden. Early acquisition of geomechanical data, including extended leak-off tests, is recommended.
- Regular risk assessments should be conducted to guide ongoing operational and monitoring strategies effectively.

3. Sleipner Project

The Sleipner CCS Project in the Norwegian North Sea began in 1996. Since then, more than 23 million tonnes of CO2 have been injected through a single extended-reach well, and permanently stored in the Utsira Sand saline aquifer (Figure 3).

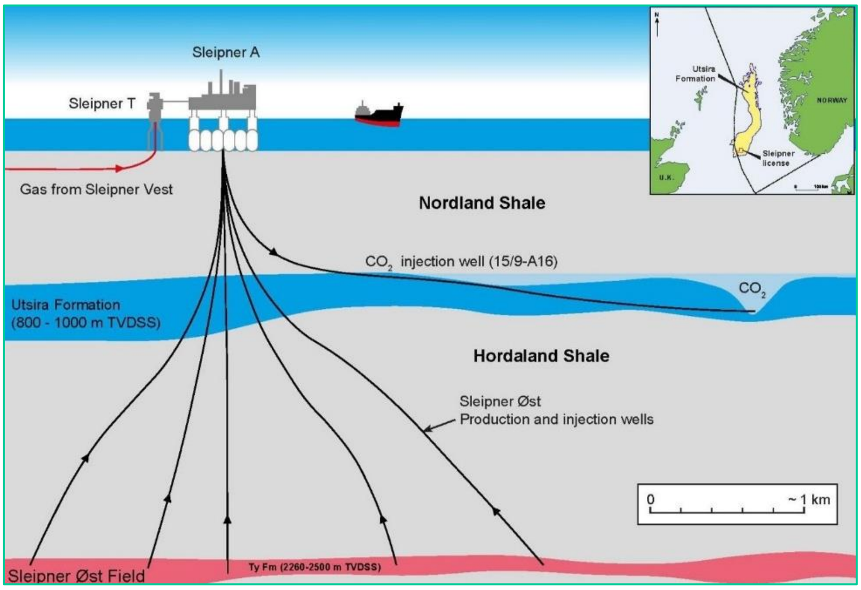
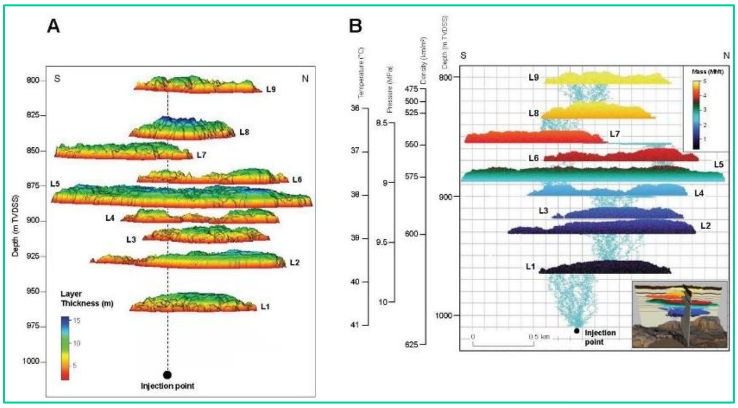


Figure 3: CO2 injection into the Utsira formation Saline aquifer. © (Soloman, S., 2007, Security of CO2 storage in Norway: Bellona Foundation Fact Sheet, Bellona, 4 p.)

The project's success revealed many important lessons, including:



- The CO2 plume migrated through sand layers and successive intraformational shales, forming a nine-tiered plume (refer to Figure 4A). By the time the initial repeat 3-D seismic survey was conducted in 1999, the plume had already reached the primary top seal. This observation provided valuable insights into how gas chimneys and microfractures influence the vertical migration of CO2 through shales.

Figure 4: (A) 3D reservoir simulation model (viewed from the SE) of the Sleipner CO2 plume as of July 2002, illustrating the nine tiers above the injection point at 1012 m TVDSS. The CO2 successfully migrated in each layer before reaching a critical thickness then leaking through the intraformational shale baffle into the layer above. (B) Modelled plume shown from the east, showing layer thicknesses, migration pathways, reservoir temperature, pressure, and CO2 density. The colour bar shows total mass of CO2 injected as of July 2002 (Cavanagh and Haszeldine, 2014)

- 4-D time-lapse seismic was crucial for monitoring the plume's growth and clearly depicted its multi-layered development over time.
- CO2 behaves as a dense, supercritical fluid with gas-like characteristics at Sleipner, where its pressure, temperature, and density vary within the plume, leading to uncertainties in storage capacity (Figure 4B).
- Buoyancy primarily traps most CO2, though other mechanisms like residual trapping (expected to account for >30% storage after 20 years), solubility trapping (important after 100 years), and mineralisation (predicted to reach 22% after 10,000 years) also play roles.

4. Snohvit Project

Snøhvit has proven that, even after steadfast study and monitoring using top-level technology and engineers, actual behavior of what has been studied can turn out to be substantially different and replacement plans may need to be implemented with speed in order to avoid catastrophe.

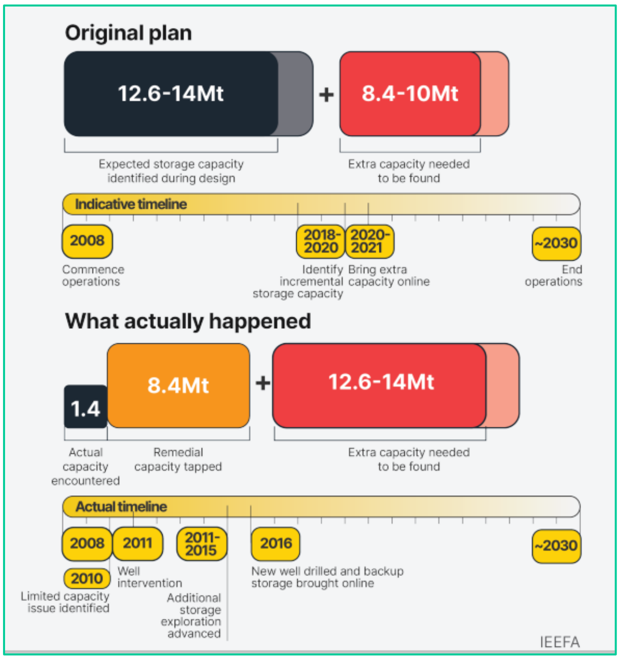


Figure 5: Storage capacity plan ©13 June 2023, IEEFA, Norway's Sleipner and Snøhvit CCS: Industry models or cautionary tales?

Original Plan:

- Inject in safe formation underneath gas producing area.
- Sufficient capacity for about 18 years of production
- Use time to find suitable follow-on storage space.
- Switch over to new area once original layer is full.

Remedial Plan:

- Find a quick fix layer for storage to resume operations.
- Determined only good for about 4-6 years of operations, i.e. to about 2016.
- Immediately prospect for new CO2 storage, starting 2011
- Invest in developing new well and infrastructure, 2016.
- Invest at least US$225 million

Snøhvit, have proven that, to assure long-term secure CO2 storage:

- Ongoing monitoring and verification of storage site integrity is imperative.
- Backup plans must always be available in case storage formations do not behave as anticipated.
- Companies that invest in and operate these fields need to have the financial and technical resources at the ready to address deficiencies, deviations, and unexpected performance.
- Clear regulations and requirements are necessary across the entire CCS life cycle to maintain integrity.
- Keeping CO2 securely in the ground, permanently, cannot be guaranteed.

5. Quest Project:

"This is the first commercial-scale carbon capture and storage (CCS) project in the world, located in an industrial processing plant. It is intended to permanently store and collect about one million tons of CO2 per year, which is the same as the emissions from about 250,000 cars" ©globalccsinstitute.com

- Quest represents Shell's commitment to integrated CCS operations, demonstrating its role in advancing technology to combat climate change.
- It holds the record for CO2 capture in hydrogen production among CCS/CCUS projects.
- Quest serves as a global model for deploying CCS in oil sands and industrial operations.
- Before Quest, securing subsurface rights for CO2 sequestration in Alberta was unprecedented.
- Transparent monitoring and community engagement were pivotal to Quest's success.
- Integrating the capture plant into the hydrogen manufacturing unit (HMU) was crucial for Quest's operational success.
- The site selection ensured minimal potential leak paths with excellent seals.
- Ongoing transparent monitoring ensures the safety of the Quest storage site.
- Quest has provided valuable lessons and best practices, reducing the time, effort, and cost for future CCS projects globally.

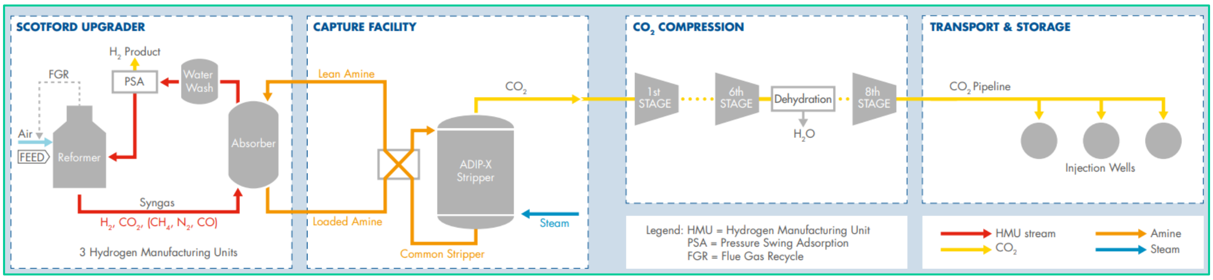


Figure 6: Basic overview of Quest's lineup ©globalccsinstitute.com

6. K12-B Project

The K12-B gas field is situated in the Dutch sector of the North Sea, about 150 km northwest of Amsterdam. Discovered in 1982, gas production began in 1987, and Neptune Energy Nederland B.V. currently operates the platform. Gas is extracted from the Upper Slochteren Formation at a depth of approximately 3800 meters below sea level, where the reservoir temperature reaches around 128 ºC. The gas stream, containing 13% CO2, undergoes CO2 removal directly offshore on the platform.

- The K12-B gas reservoir is the first and currently the only gas reservoir in the Netherlands where captured CO2 has been reinjected.
- Safe reinjection of CO2 into depleted gas fields is technically feasible and can be conducted concurrently with exploration and production activities.
- Over a decade of continuous CO2 injection has been successfully demonstrated, supported by numerous risk assessment studies.
- Findings from this comprehensive scientific study on CO2 reinjection can inform future global carbon capture and storage initiatives.
- The project comprised multiple smaller initiatives funded by various bodies, forming a successful ongoing multi-year endeavor.
- This approach has proven effective for launching a long-term project without requiring full funding upfront.

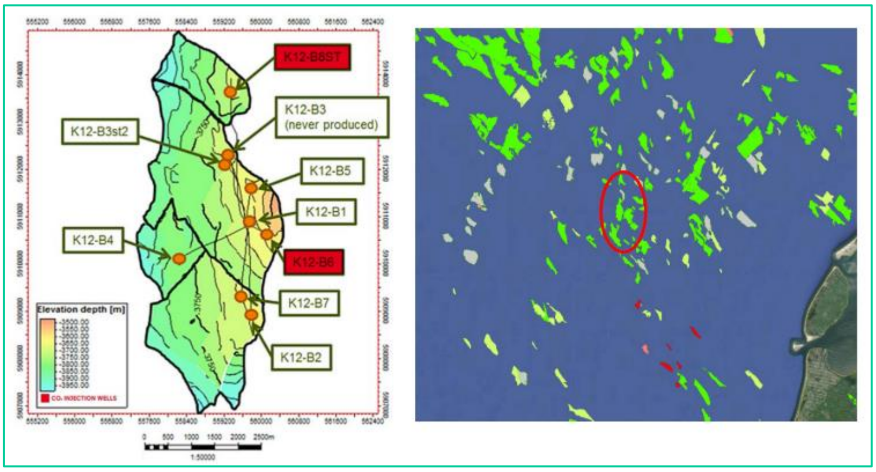


Figure 7: Right: Compartment structure of the K12-B gas field. The CCS took place in the Northern compartment (K12-B8ST) and the adjacent compartment (K12-B6). The CO2 injection wells are indicated by red labels, and the gas producing wells with white labels. Left: Location overview, with Noord Holland and the island of Texel in the South-East corner. © Fr CO2 07, 13 Years of Safe CO2 Injection At K12-B,

7. Aquistore Project

In 2009, Aquistore was originally set up to store up to 600 tons/day of CO2 captured from an oil refinery located within the city of Regina, Saskatchewan. The CO2 was to be transported via pipeline and injected to a depth of 2200 m approximately 8 km outside of the city limits. The Aquistore CCS project provides valuable insights into carbon capture and storage. Here are some key takeaways:

- Research collaborations are essential for CCS projects, enhancing project value and enabling organizations without sufficient funds to contribute through in-kind research.

- First-generation CCS demonstration projects should aim to develop a global capacity for CCS, facilitating knowledge transfer across nations and organizations to benefit future projects.
- Independence is crucial in CCS projects. The Aquistore SERC, founded in 2009, emphasizes the importance of an independent technical advisory group focused solely on project success.
- Selecting a suitable geological site for CO2 injection requires three primary criteria: sufficient permeability for continuous injection, capacity to store large volumes of CO2, and effective trapping mechanisms including caprock integrity.
- Monitoring and verification techniques are essential to track CO2 flow and ensure storage efficacy, as demonstrated by Aquistore's ongoing observations.
- Effective regulatory frameworks and legal agreements are essential for managing permits, liability, and compliance in CCS projects, as highlighted by Aquistore.
- Knowledge sharing is critical in CCS initiatives to disseminate research findings and best practices, advancing technology and supporting future CCS projects globally.

Conclusions

- The lessons learned from active CO2 injection sites, spanning from large-scale EOR projects to smaller-scale pilots, underscore the complex dynamics of carbon capture and storage (CCS) initiatives.
- These insights highlight the critical importance of geological suitability in site selection, robust monitoring, and verification protocols for ensuring secure storage, and effective public engagement strategies to build community support.
- Regulatory frameworks and legal considerations are pivotal in navigating permitting, liability, and compliance challenges throughout the project lifecycle.
- By synthesizing experiences from diverse projects like Gorgon, In Salah, Sleipner, Snohvit, Quest, and K12-B, this review informs future CCS endeavours, enhancing implementation strategies and advancing global efforts towards carbon neutrality and climate change mitigation.
- Continued knowledge sharing and collaborative research are essential for refining CCS technologies and addressing ongoing challenges in sustainable CO2 management.

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