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Norway's Sleipner and Snøhvit CCS: Industry models or cautionary tales?

Examining the geologic storage risks of CSS in Norway

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Industry hype for Norway's CCS

Industries and governments alike, worldwide, cite these two Norwegian projects at proof that subterranean carbon dioxide (CO_2) storage works.

Glowing testimony and citations have been read into public record in parliamentary and congressional committees globally.

Hundreds of offshore CCS projects are proposed or under development globally, representing 240mtpa of CO_2 injections and projected to cost $100s of billions.

Premise for this research

There has been little in the way of objective debate on the cost and risks of the geologic storage, particularly on a holistic, lifecycle basis.

Most discussion of the Norwegian pair's operational performance is confined to academic papers and technical journals

Are these two projects actually well-performing models for CCS? Or is there more to know? The answer has great implications for the world.

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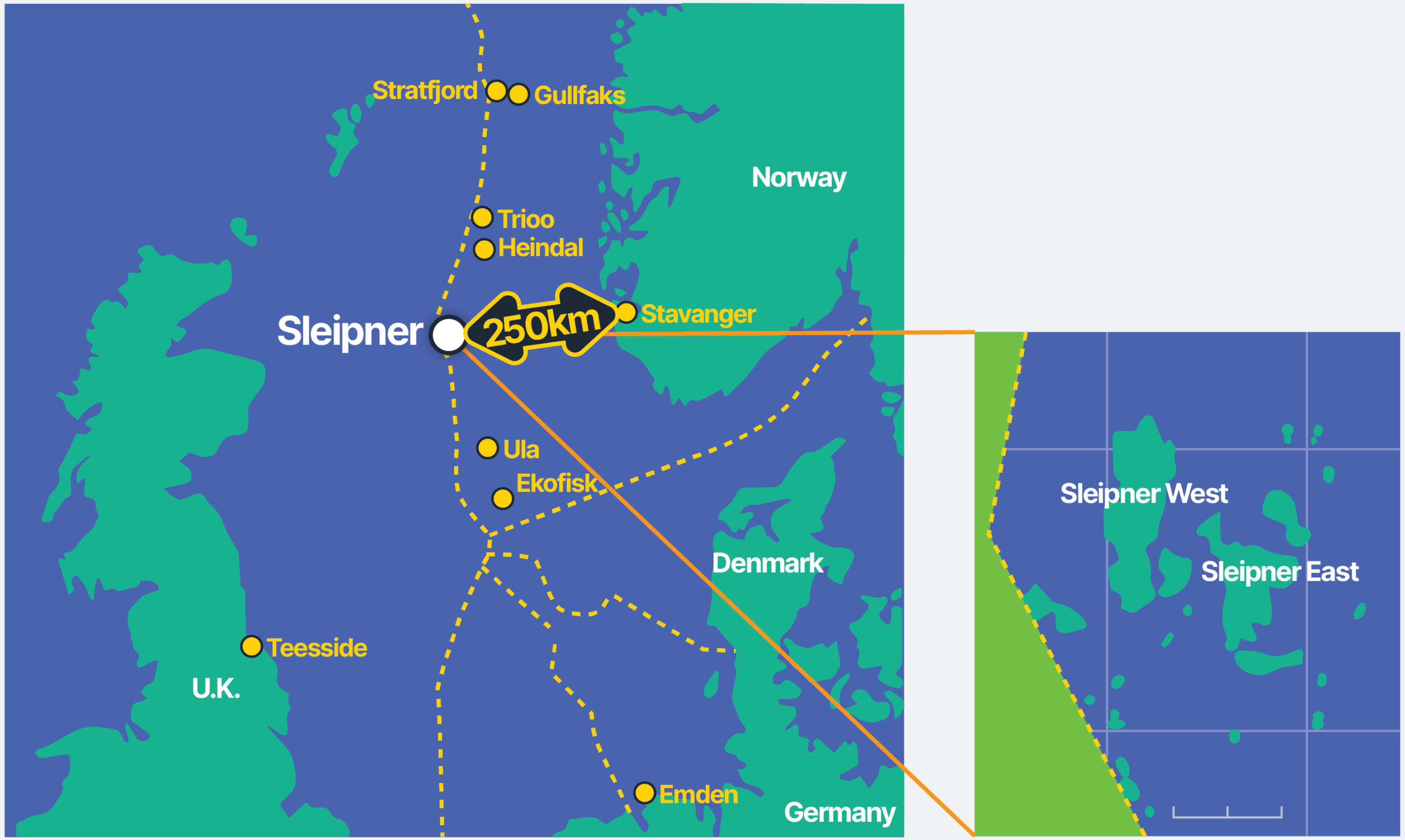
Norway CCS Project Overviews

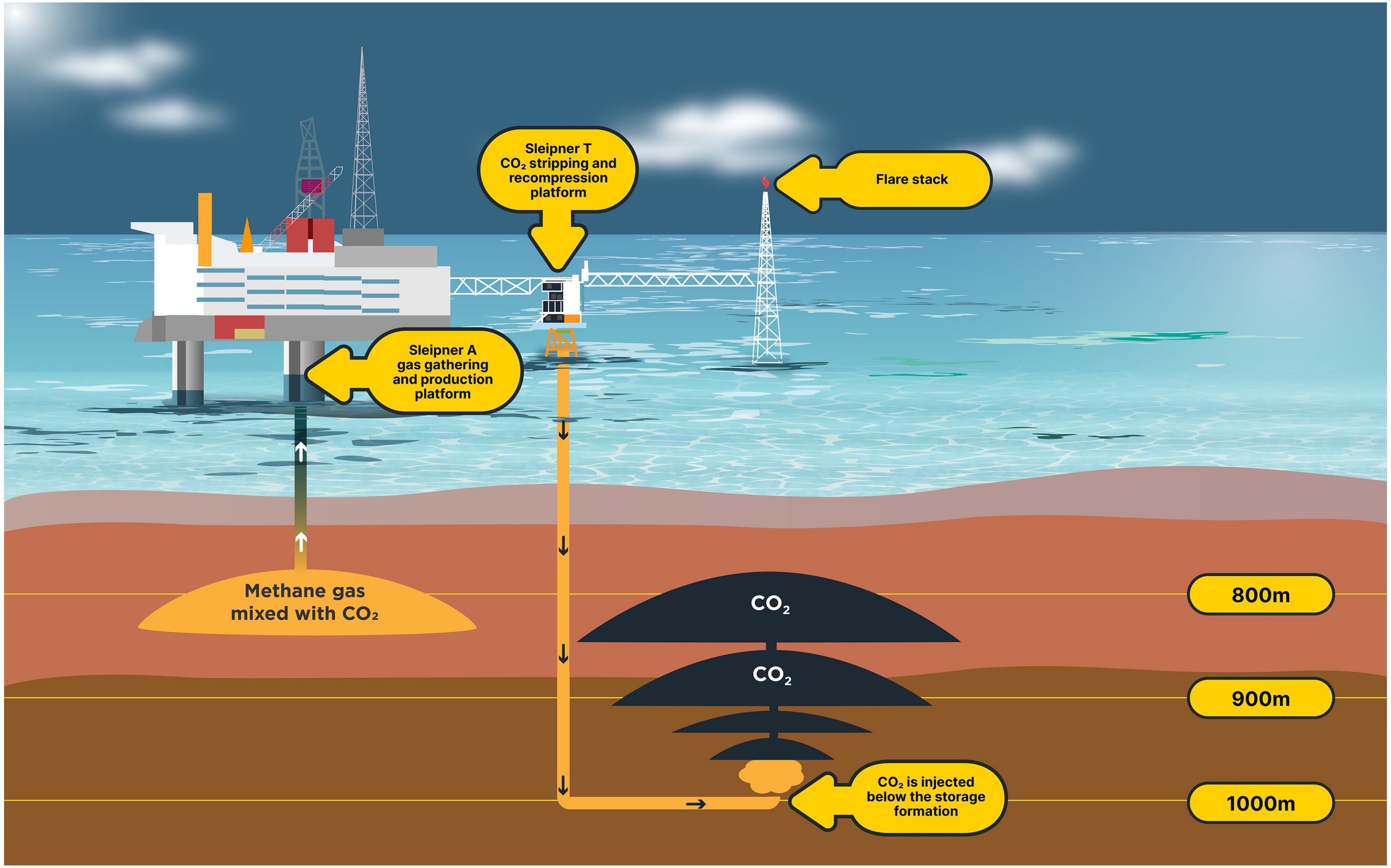
Sleipner Project Overview



Source: Zhu Laboratory, Indiana University Bloomington. IEEFA

- August 1996
- Natural gas production field with 4% to 9% CO_2 content
- 250 km offshore
- 80m-100m water depth
- Dedicated CO_2 process platform offshore
- 12km CO_2 pipeline
- Single injection well
- 0.9mtpa CO_2 injected currently
- About 22Mt CO_2 underground now
- $92m investment cost
- Driven by Norway CO_2 tax initiated 1991

Sleipner: schematic of CO_2 storage operations



Source: Geological storage of CO_2: project design and global scale-up. Ringrose. March 29, 2021.

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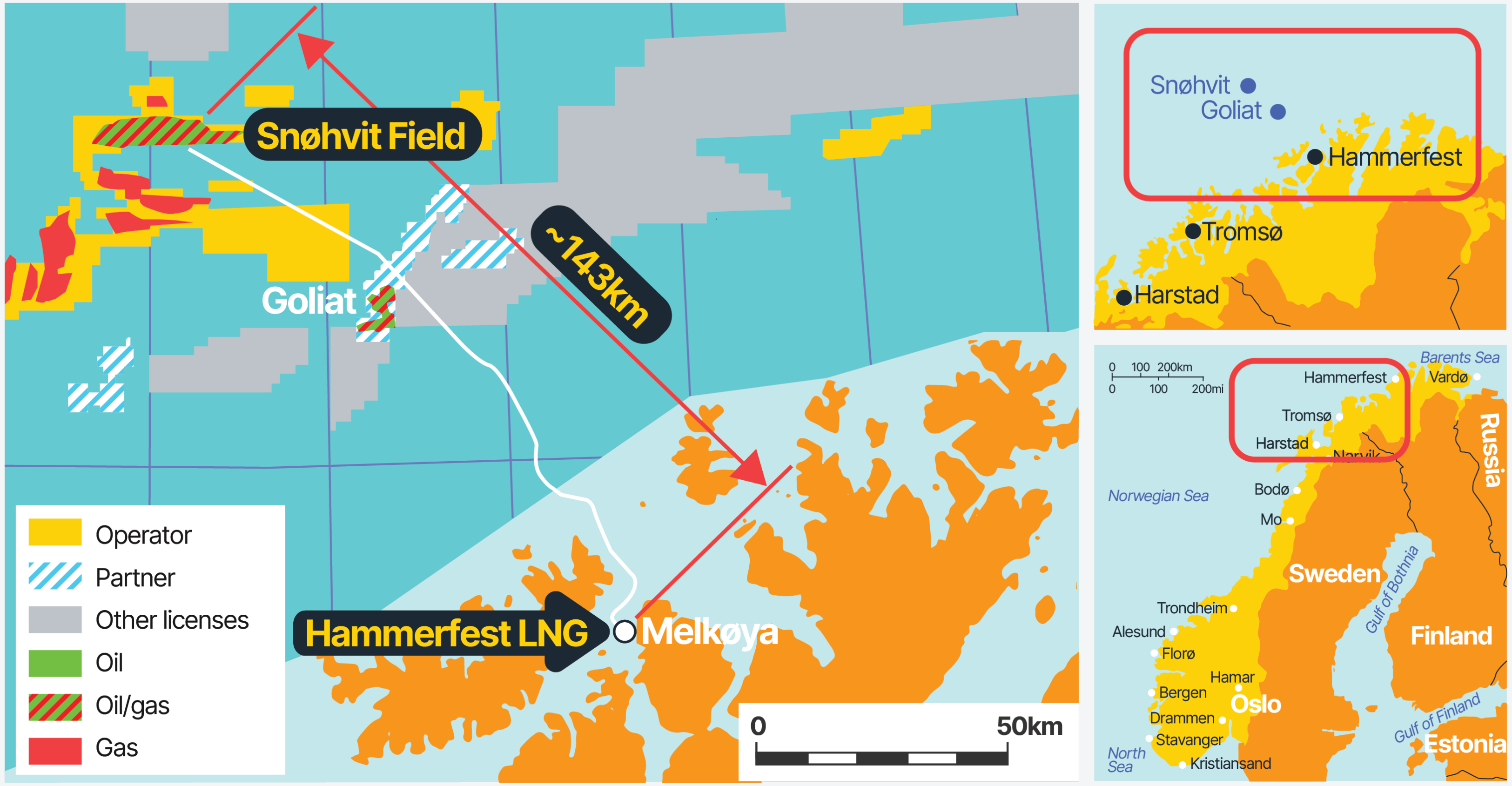
Shøhvit Project Overview



Sources: Snøhvit location map - Adapted from Statoil as referenced in the article, Statoil announces giga-investment in northernmost ever oil field. The Barents Observer. December 5, 2017.
General Norway map – WorldMap1.com. https://www.worldmap1.com/map/norway/hammerfest-map.asp

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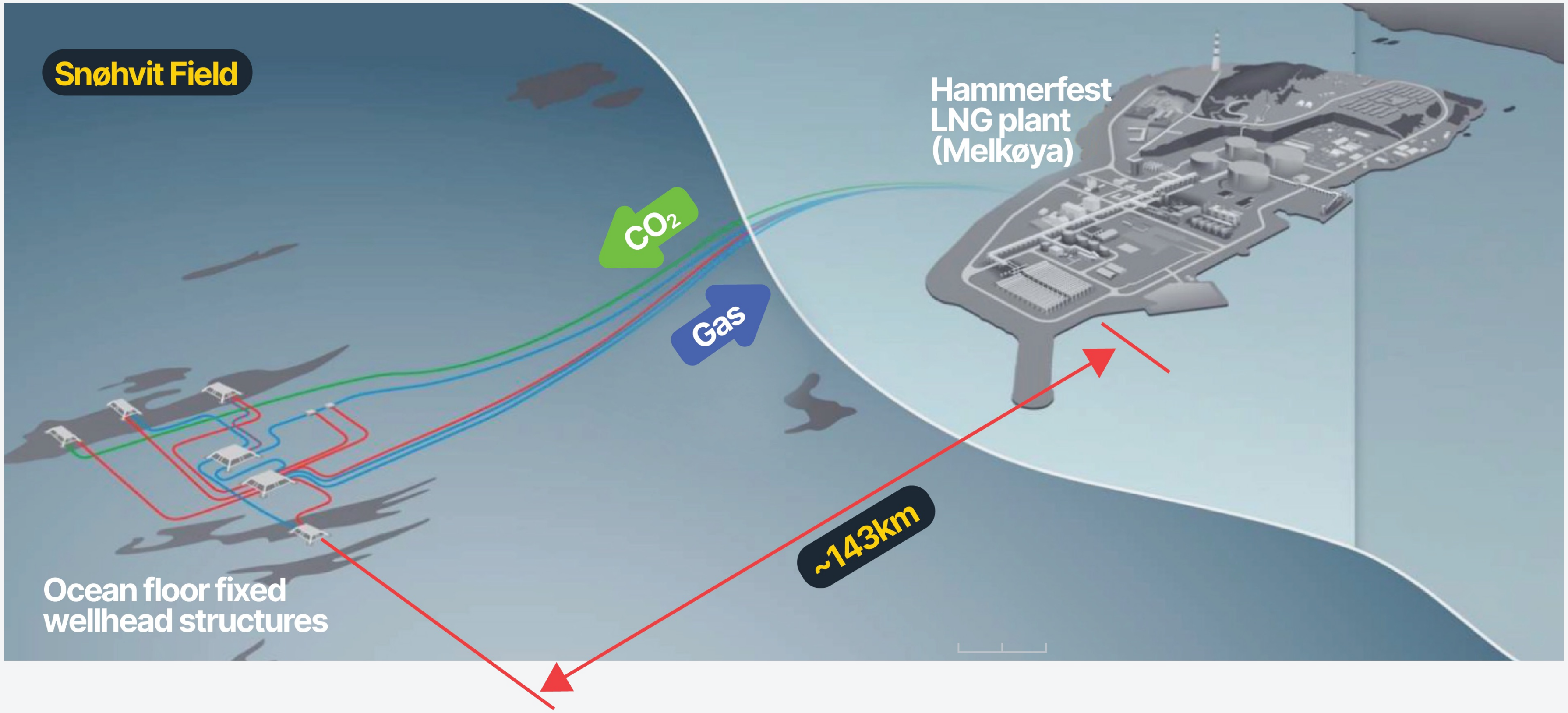
- April 2008
- Natural gas production field with 5% to 8% CO_2 content
- 143km offshore
- 300m water depth
- Onshore CO_2 processing
- 143km CO_2 pipeline
- 0.7mtpa CO_2 injected
- Using third CO_2 storage site now
- About 8-9Mt CO_2 underground in aggregate
- $191m investment[7]

Snøhvit: schematic of CO_2 storage operations



Source: Equinor and Norwegian University of Science and Technology. Ensuring safe storage operations: learning from Sleipner and Snøhvit. Ringrose. Baltic Carbon Forum 2020. October 14, 2020.

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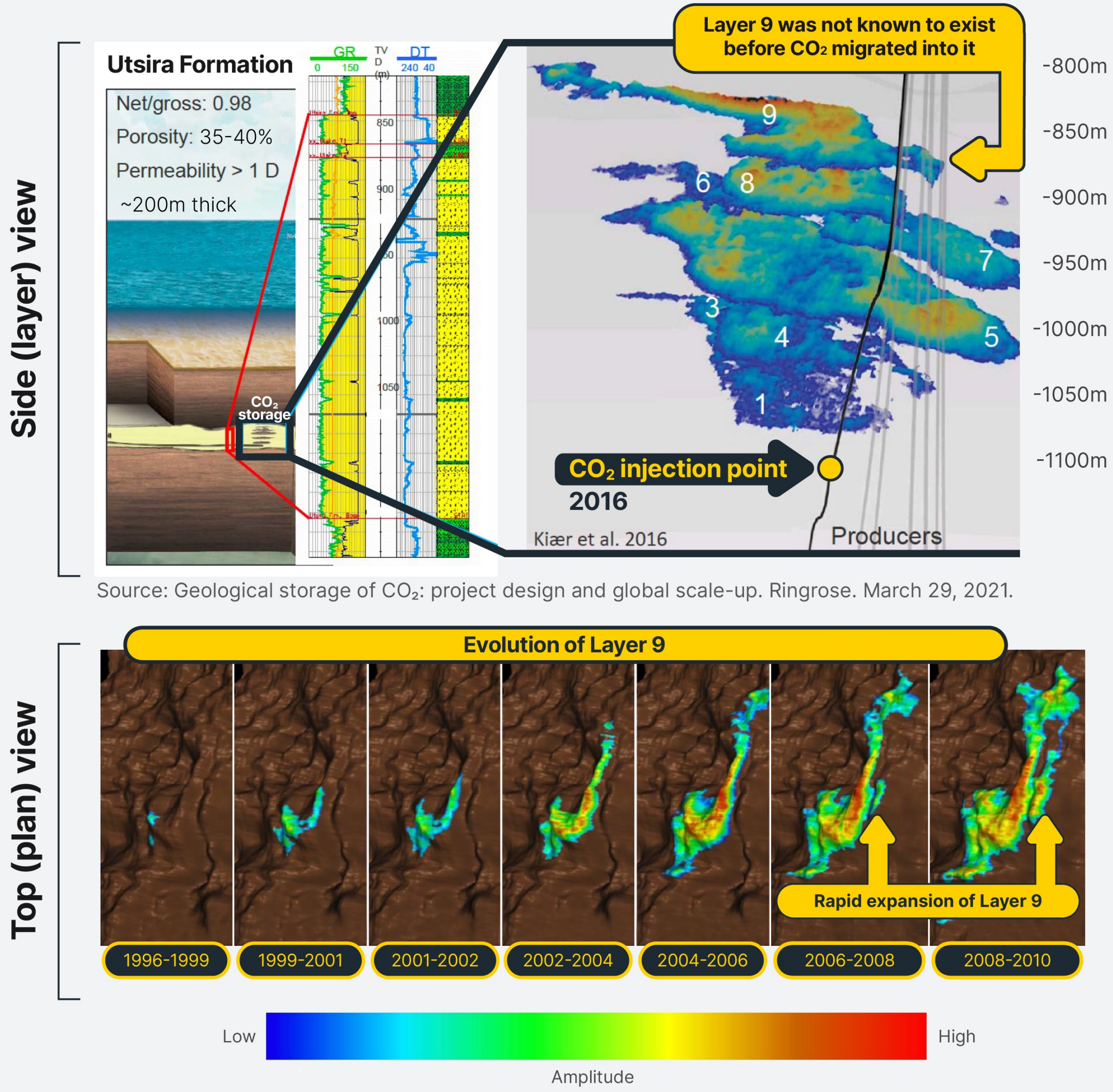
Sleipner's Challenges

Eight CO_2 storage layers become nine

- Original geophysics concept was that CO_2 would gradually percolate up through a number of shaly layers over a period of many years
- This configuration was identified through preliminary seismic studies and calculations
- Instead, in less than three years, CO_2 had moved all the way up to underneath the caprock
- CO_2 accumulated in a previously unidentified layer 9
- At some point after 2004, this accumulation accelerated to large volumes
- The horizontal boundaries of Layer 9 remain unknown



Source: Geological storage of CO_2: project design and global scale-up. Ringrose. March 29, 2021.

Source: Statoil ASA. Sleipner – 20 years of successful storage operations and key learning for future projects. Skalmeraas. June 29, 2016.

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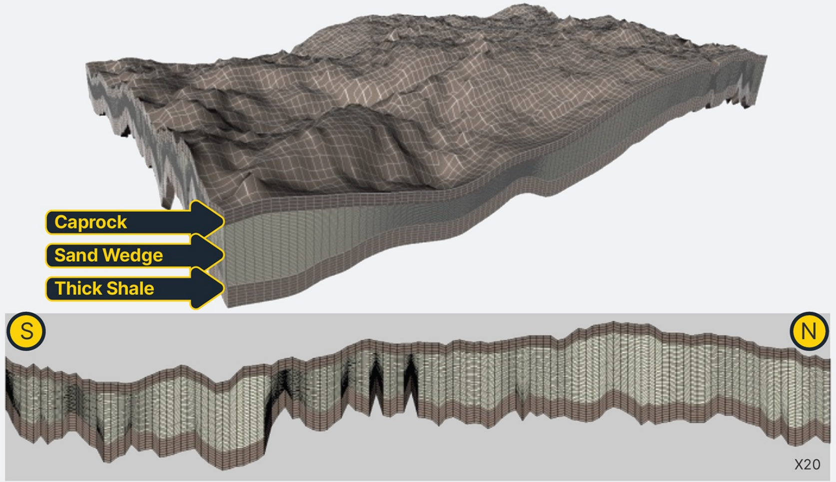
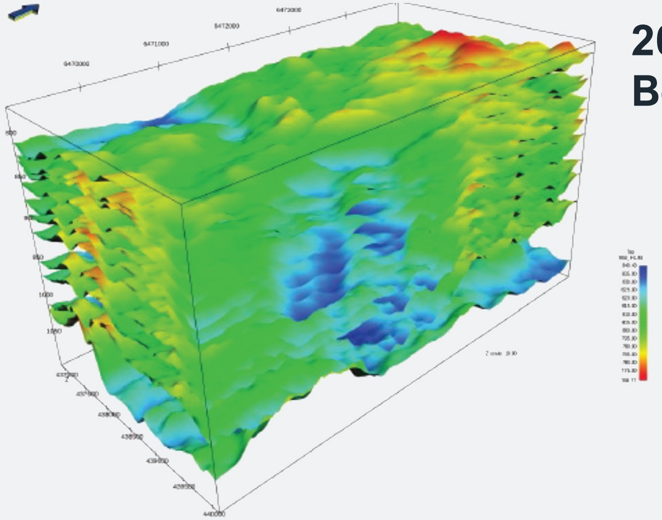
How much CO_2 is actually stored and where?

- Repeated seismic imaging studies have seen the CO_2 plume remain centered above the injection point but grow in horizontal area
- Depth of the plume has proven challenging to measure
- Only calculations based on the seismic data can verify whether the CO_2 injected is actually stored there.
- Equinor and national technical universities have been engaged in developing ”benchmark” models of the plume and geology in an attempt to figure out how much CO_2 is there
- More data is being collected and more models are being created
- Analysis is essentially being crowdsourced

2011 Benchmark



Source: Energy Procedia. Benchmark calibration and prediction of Sleipner CO_2 plume from 2006 to 2012. Cavanagh. Volume 37. 2013, p. 3529-3545. 2013.



2019 Benchmark

Source: Equinor. Sleipner Benchmark 2019. CO_2 DataShare. October 2022.

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Snøhvit’s Challenges

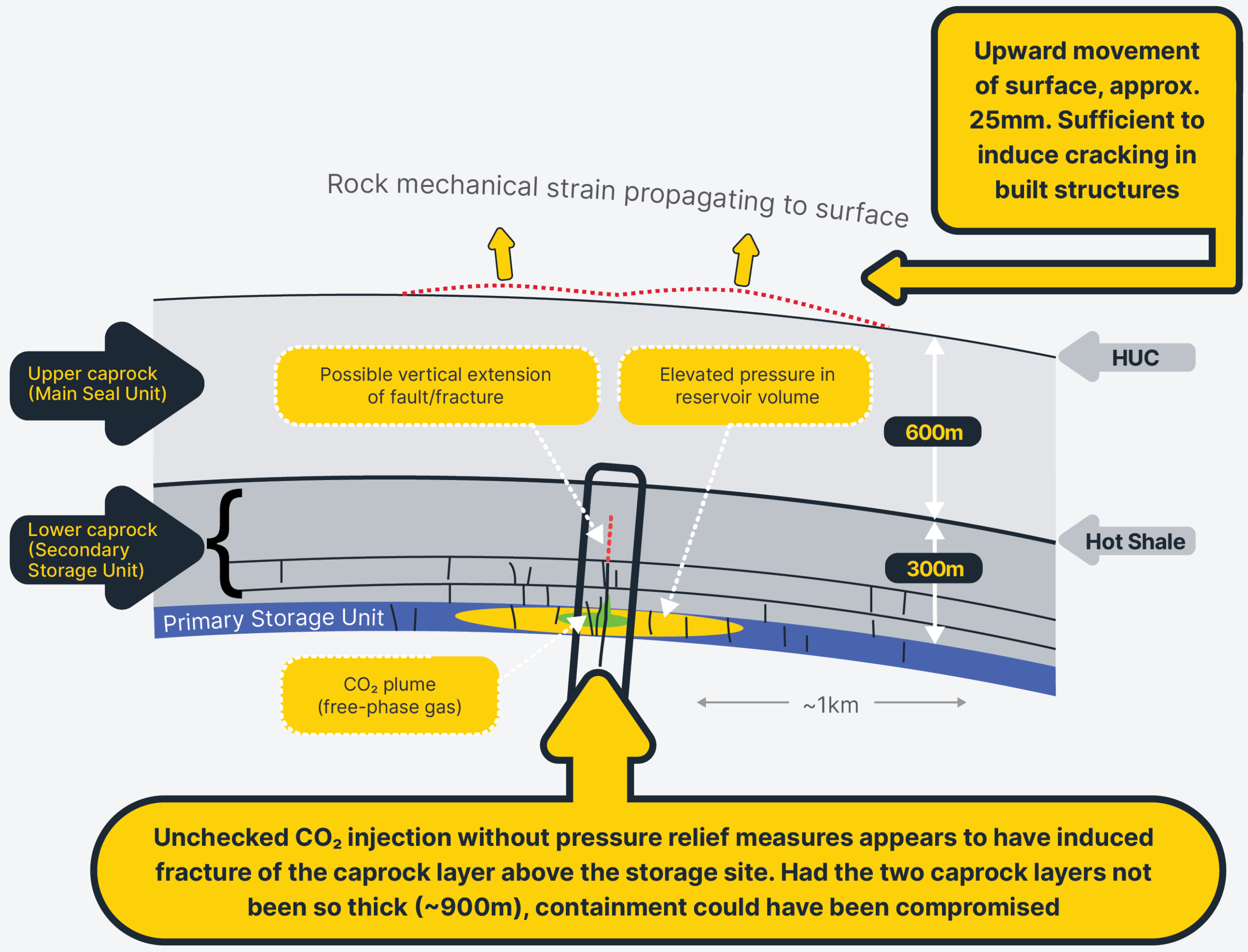
Snøhvit experiences trouble very early

- CO_2 injections commenced August 2008
- Targeted formation is meant to have 18 years capacity
- Only 18 months into operations, pressure in the storage space rose precipitously, risking geologic failure
- Storage needed to be suspended and a well intervention conducted to find out what is causing the trouble
- The entire nearly $7bn Snøhvit-Hammerfest value chain project is in jeopardy because of this.

Caution required due to In Salah, Algeria experience

What happened?

- Massive pressure rise happened early on in operations
- Jeopardized gas production
- Kept injecting
- Detected geologic failure due to pressure drop
- Injections permanently suspended
- Was deemed okay since it was voluntary storage activity
- CO_2 again vented to atmosphere



Sketch illustrates main geomechanical observations around injection well KB-502

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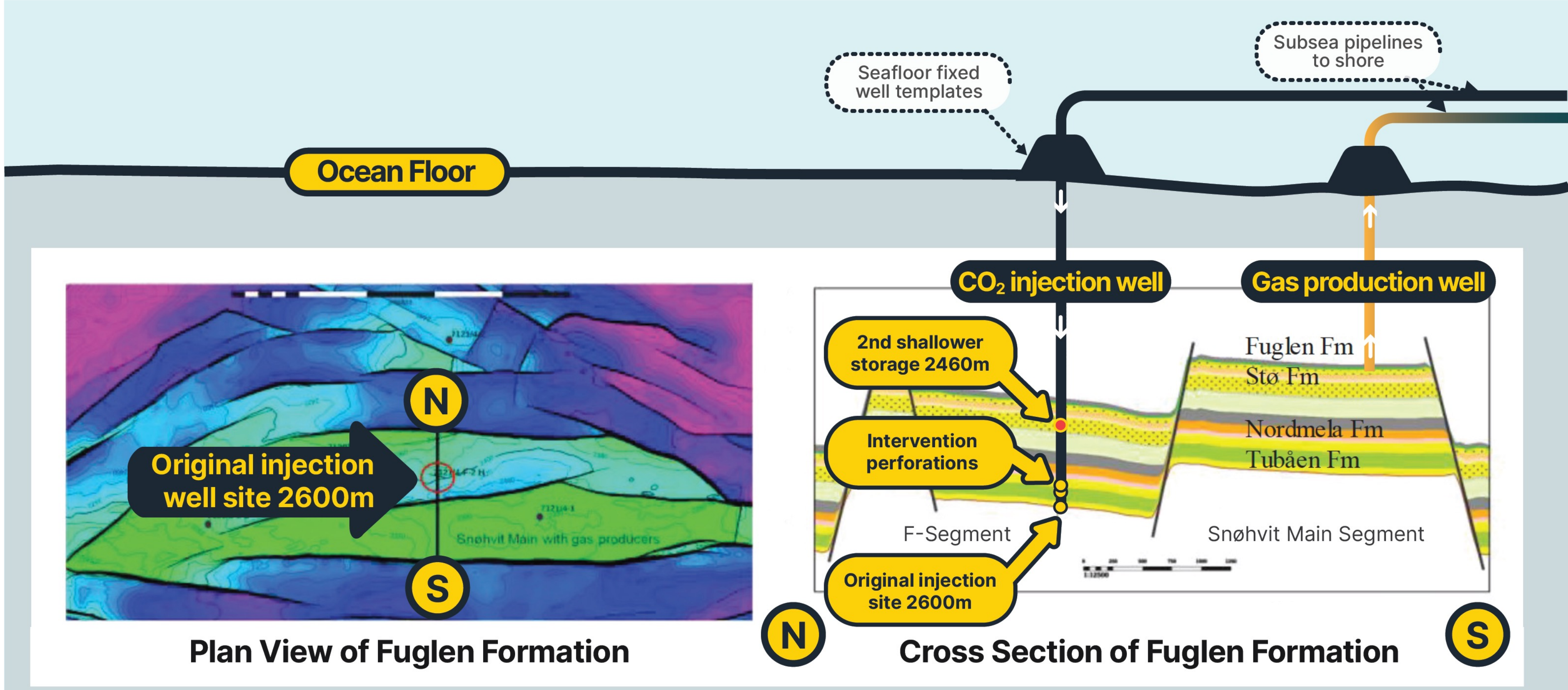
Source: Energy Procedia. The In Salah CO_2 storage project: lessons learned and knowledge transfer. Ringrose et al. No 37, 2013, p. 6226-6236.

Snohvit's target storage layer rejects CO2

Interventions List

- ✗ Blocked well?
- ✗ Salts forming at interface?
- ✗ Reperforate well to reduce pressure?
- ✓ Plug well
- ✓ Try new perforations in a shallower stratum?
- ⚠ But try not to interfere with gas producing layer



Source: Energy Procedia. Snøhvit: The history of injecting and storing 1mt CO_2 in the fluvial Tubåen formation. Hansen et al. No 37, 2013, p. 3565-3573. Annotated by IEEFA.

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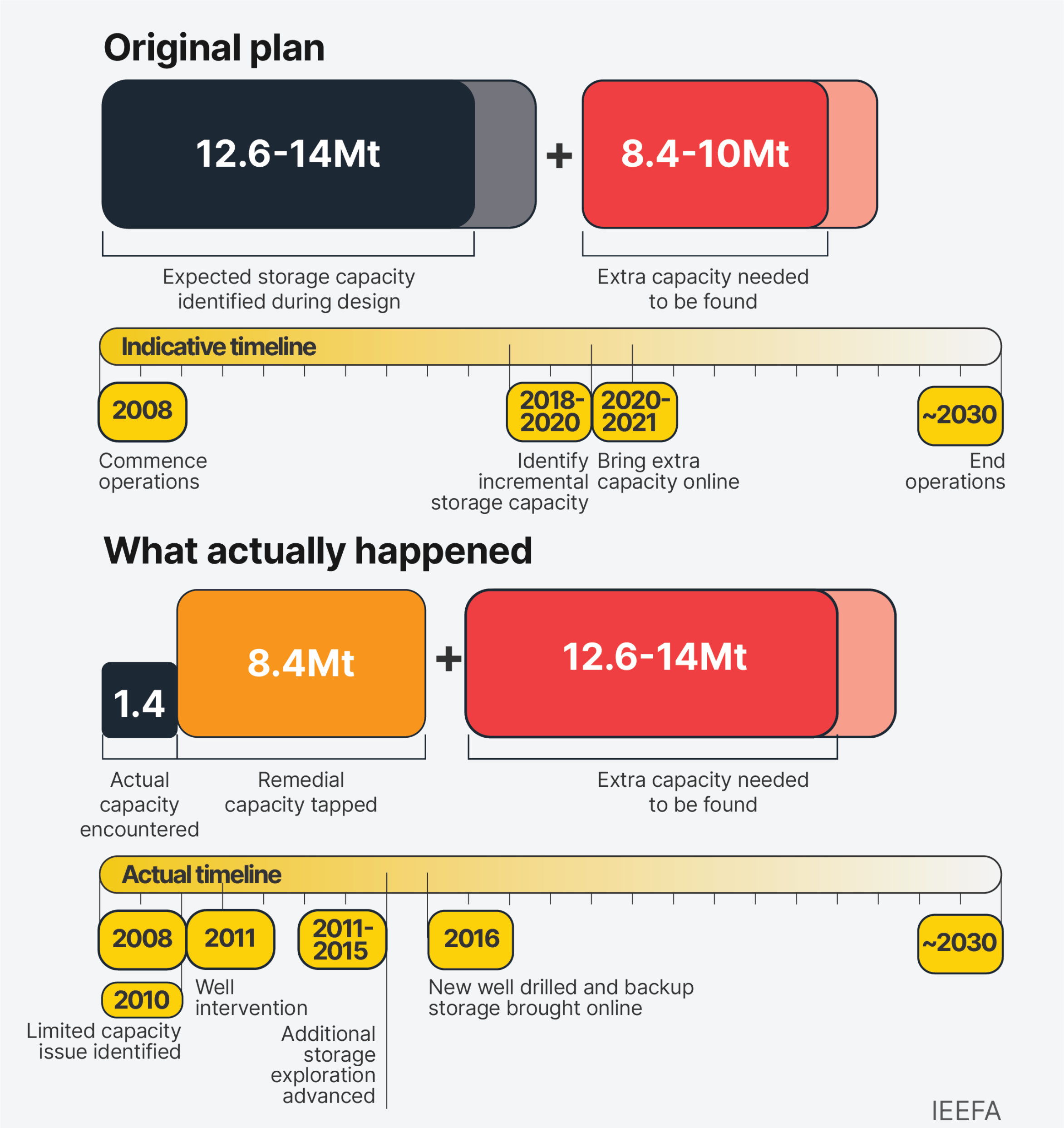
Reduced storage capacity necessitated finding new

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 CO_2 storage, starting 2011
- Invest in developing new well and infrastructure, 2016
- Invest additional at least US$225 million

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Challenges and Implications

Challenging conclusions

- Putting CO_2 back into the ground is proving to be far more technically complex and filled with uncertainty
- Geophysicists and engineers admit is more difficult to put something back in the ground than to extract it
- The ongoing costs of monitoring, studying and contingency plans are material
- In the event of a performance deviation, need for action may be immediate, requiring high levels of technical and financial resources as well as specialist equipment
- Even with the best talent and resources, experts still don’t know whether the CO_2 will behave as needed.

Technical implications

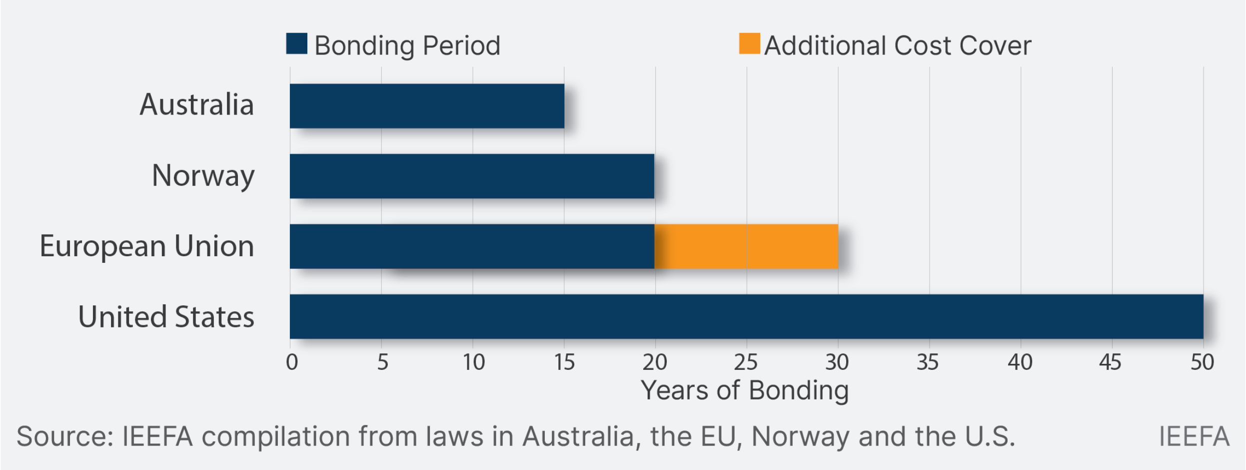
- Storage sites require extensive exploration, engineering and contingency planning – before, during and after closure
- Even using the most advanced tools available, surveying and modelling are inherently inaccurate; the possibility of missing critical subsurface features is always present
- Multiple forms of surveying, monitoring and modeling are required at regular intervals
- Vigilance must be maintained constantly, including after closure

Scale implications

- It is challenging to see how Sleipner or Snøhvit can be used as proxies for projects 10 time or larger in storage capacities
- The number of geologic anomalies encountered at a storage site is more likely to be proportional to is area
- This means larger-scale sites will require larger-scale engineering and monitoring efforts with more points where things could go wrong
- There are direct implications for the costs and resource requirements
- As the tonnage injection rates of CO2 increase so does the risk of failures, leakage

Regulatory implications

- Only a handful of countries have any form of CCS regulation
- Some considering CCS do not
- Each of those reviewed has recognized the need for long-term bonding provisions to cover the cost of monitoring, maintenance and intervention post well closure
- Most have provisions to waive those bonds at the regulators’ discretion



Regulatory implications

- Potential for rapid and/or large-scale variations of CO_2 storage site performance mean that regulation needs to be proactive
- Regulators' vigilance needs to be maintained across lifecycle
- Regulators need to be staffed and equipment with a commensurate level of sophistication as those they oversee
- Carbon taxes made Sleipner and Snohvit worthwhile investments; finite budgeted subsidies may not work the same way
- Leakage from subsurface storage areas, meant to permanently dispose of CO_2, has impacts both on a company's decarbonization targets, but, more importantly, directly upon a countries Paris Agreement net zero commitments.

Conclusions

Sleipner has proven that, even after steadfast study and monitoring using top-level technology and engineers, injected CO_2 can move to unexpected places and behave in unexpected ways even years after what appears to have been nominal operations

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.

Sleipner and Snøhvit, have proven that, to assure long-term secure CO_2 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 CO_2 securely in the ground, permanently, cannot be guaranteed

IEEFA Carbon Capture and Storage Research

- The carbon capture crux: Lessons learned
  Compendium of global CCS projects across applications and technologies
  Bruce Robertson and Milad Mousavian
- Gorgon carbon capture and storage: The sting in the tail
  Bruce Robertson and Milad Mousavian
- Carbon capture's methane problem
  David Schlissel and Dennis Wamsted
- The ill-fated Petra Nova CCS project: NRG Energy throws in the towel
  Suzanne Mattei and David Schlissel
- The CCUS entourage in Southeast Asia: A convenient ride to delay the hard questions?
  Putra Adhiguna
- Proposed CCS projects need careful review for cost, technology risks
  Dennis Wamsted and David Schlissel
- CCS for power yet to stack up against alternatives
  Christina Ng and Michael Salt
- Carbon capture to serve enhanced oil recovery: Overpromise and underperformance
  Bruce Robertson and Milad Mousavian
- For additional research, reporting and commentary refer to IEEFA Carbon Capture and Storage Analysis

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