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Integrated Decision-Based Modelling for CO_2 Storage Site Evaluation: A New Paradigm

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Abstract

Oil and gas reservoir modelling and CO_2 storage modelling are both fundamental to subsurface engineering but serve distinct objectives—hydrocarbon production versus long-term climate mitigation. Despite employing similar geological and simulation tools, the two fields differ significantly in fluid behavior, operational timeframes, and risk profiles. Oil and gas models focus on optimizing recovery over decades, while CO_2 storage modelling prioritizes the safe, permanent containment of CO_2 over centuries, accounting for complex geochemical and geomechanical interactions.

This study introduces a novel decision-based modelling framework for evaluating CO_2 storage sites, designed to address uncertainty and risk systematically. The workflow comprises four stages: (1) an uncertainty assessment matrix that categorizes key subsurface uncertainties, (2) risk identification and ranking using both qualitative and quantitative methods, (3) a focused evaluation of critical risks to guide data acquisition and model refinement, and (4) scenario-based modelling to simulate a range of geological and operational conditions. This approach ensures key risks are explicitly incorporated into decision-making, enabling robust, transparent site selection.

The framework was applied to a ~3,500 km² basin in Saudi Arabia, supported by 3D seismic data and 35 wells—most located on the basin's perimeter. Key storage suitability factors—reservoir depth, salinity, structural dip, reservoir and seal quality—were ranked as low, medium, or high risk. Depth and reservoir quality posed low risk. The salinity, structural dip, and seal continuity/thickness were considered medium risk while the seal lithology and facies were highly variable and considered high risk.

By overlaying medium-risk parameters maps (e.g., salinity, dip, seal continuity), a low-risk "sweet spot" was delineated. Though seal lithology remained uncertain due to sparse data, further analysis indicated moderate overall seal risk across identified sweet spot. Mud and wireline logs, combined with core data from nearby wells, revealed high-permeability sandstones and low-permeability carbonates. Seal formation showed varying shale thickness (40–90 ft) within a broader 150-ft interval, with lateral facies transitions complicating risk assessment.

To address this, multiple static models reflecting alternative seal compositions (shale-, limestone-, and sandstone-dominated) were developed and used in dynamic simulations. Results showed minor leakage

potential but highlighted pressure plume expansion and increased storage capacity in certain scenarios, underscoring the importance of seal quality in performance prediction.

This risk-informed, scenario-driven approach represents a significant advancement in CO_2 storage modelling, particularly for data-limited regions. By integrating uncertainty analysis and targeted simulation, it provides a robust decision-based modelling framework for identifying secure, viable CO_2 storage sites.