Optimizing CO_2 Injection Under Geological Uncertainties in CCUS: A Lusitanian Basin Case Study

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ABSTRACT

The PilotSTRATEGY project, funded by the European Union's Horizon 2020 programme, aims on advancing Carbon Capture, Utilization, and Storage (CCUS) technologies. This study investigates optimizing CO_2 injection in the Q4-TV1 prospect of the Lusitanian Basin, offshore Figueira da Foz, Portugal. However, the presence of legacy well and intersecting faults poses risks, such as potential CO_2 leakage and reservoir pressure build-up, which require advanced modeling and optimization strategies.

A static model covering 1925 km² with a grid resolution of 250m horizontally and 10m vertically was constructed using seismic data and legacy well information (Pereira et al., 2024) in AspenTech SKUA. This model was integrated with AspenTech's Tempest MORE and ENABLE software via a macro to simulate CO_2 plume behaviour and optimize injection scenarios in the Big Loop™ framework (Jonet et al., 2023), unifying static and dynamic modeling.

Key geological features, including two major seabed-intersecting faults, were modeled to assess their roles as both barriers and conduits for CO_2 migration. The study combines dynamic modeling and Bayesian optimization to improve CO_2 injection performance under geological uncertainties.

This study employed a three-phase methodology (Figure 1) to optimize CO_2 injection in the Q4-TV1 prospect while ensuring long-term containment and safety. In the first phase, the Big Loop™ approach (Jonet et al., 2024) integrated static and dynamic modeling using Aspen SKUA and Aspen Tempest ENABLE software. Bayesian optimization (Bordas et al., 2020) was applied to maximize CO_2 injection over a 30-year period by optimizing well coordinates and perforation depths. Geological uncertainties, including 16 interlinked porosity-permeability models and fault behavior, were modeled, with bottom hole pressure constrained to 165 bars to prevent reservoir

fracturing. Scenarios where the CO_2 plume risked migration to faults or legacy wells were disqualified, concluding with the selection of an optimal well location and parameters.

Phase two involved 450 appraisal simulations to evaluate the selected scenario under varying geological uncertainties. The optimal scenario was modeled for up to 1000 years, confirming long-term plume containment away from faults and legacy wells.

In phase three, sensitivity analysis was conducted to assess the influence of key parameters such as bottom hole pressure, reservoir permeability anisotropy, and perforation depth.

The methodological approach identified an optimal CO_2 injection scenario with a 50 m perforation length at a depth of 1177–1227 m, positioned 11.7 km from the legacy well and 8.7 km from faults. This strategic placement minimized risks of leakage and fault interactions, achieving long-term plume stability with a maximum total CO_2 injection of approximately 24 million tons.

Probabilistic modeling (Figure 2) validated the scenario's robustness, revealing a percentile P_{90} injection value of 16.07 million tons, a P_{50} of 8.8 million tons, and a P_{10} of 3.9 million tons. These results highlight variability due to geological uncertainties while confirming the scenario's stability and efficiency.

Dynamic simulations emphasized the importance of optimizing parameters such as fault transmissibility, permeability anisotropy, and bottom hole pressure, which proved critical for maintaining reservoir integrity and injection efficiency. Perforation depth and thickness were essential for optimal plume dispersion and long-term containment. Sensitivity analysis reinforced bottom hole pressure as a key factor in balancing storage capacity and safety. These findings underscore the need for precise parameter control to achieve secure and efficient CO_2 storage.

This study demonstrated the integrating Bayesian optimization within the Big Loop™ framework to address geological uncertainties in CCUS projects. By incorporating the full range of static and dynamic uncertainties simultaneously into a probabilistic framework, the methodology identified optimal CO_2 injection scenarios, enhancing storage strategies in complex settings. The findings underscore the potential of Bayesian optimization to advance global CCUS initiatives.

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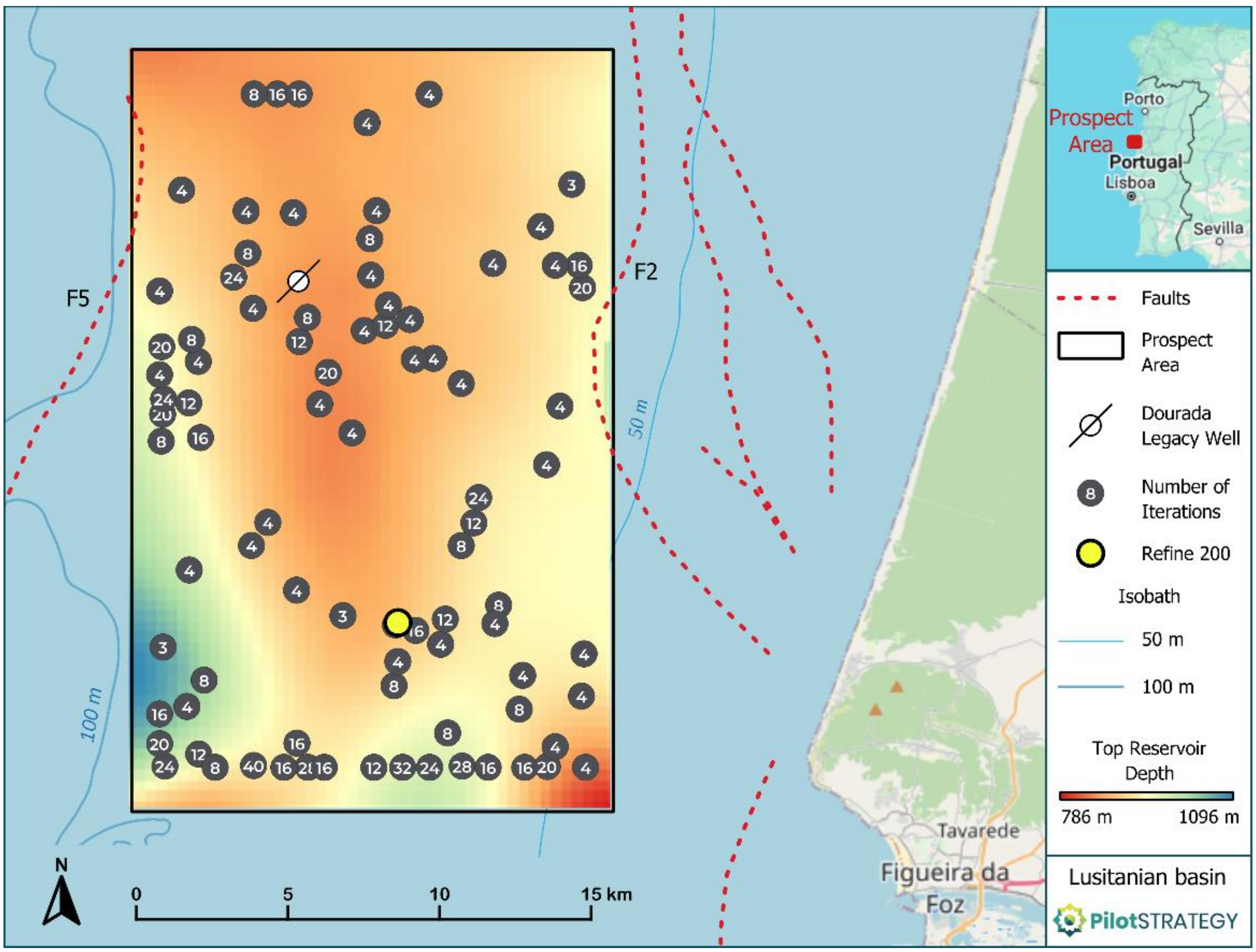

Figure 1: Map of the area of interest showing 948 scenarios for CO_2 injection well locations. Gray dots represent overlapping optimal scenarios for well placement. Scenario 200, with a capacity of 24 million tons (optimal well location), is positioned further from the legacy well and faults, enhancing safety. The map also illustrates the depth of the top reservoir (shown in color gradient), with blue representing the surrounding ocean for the case study area.

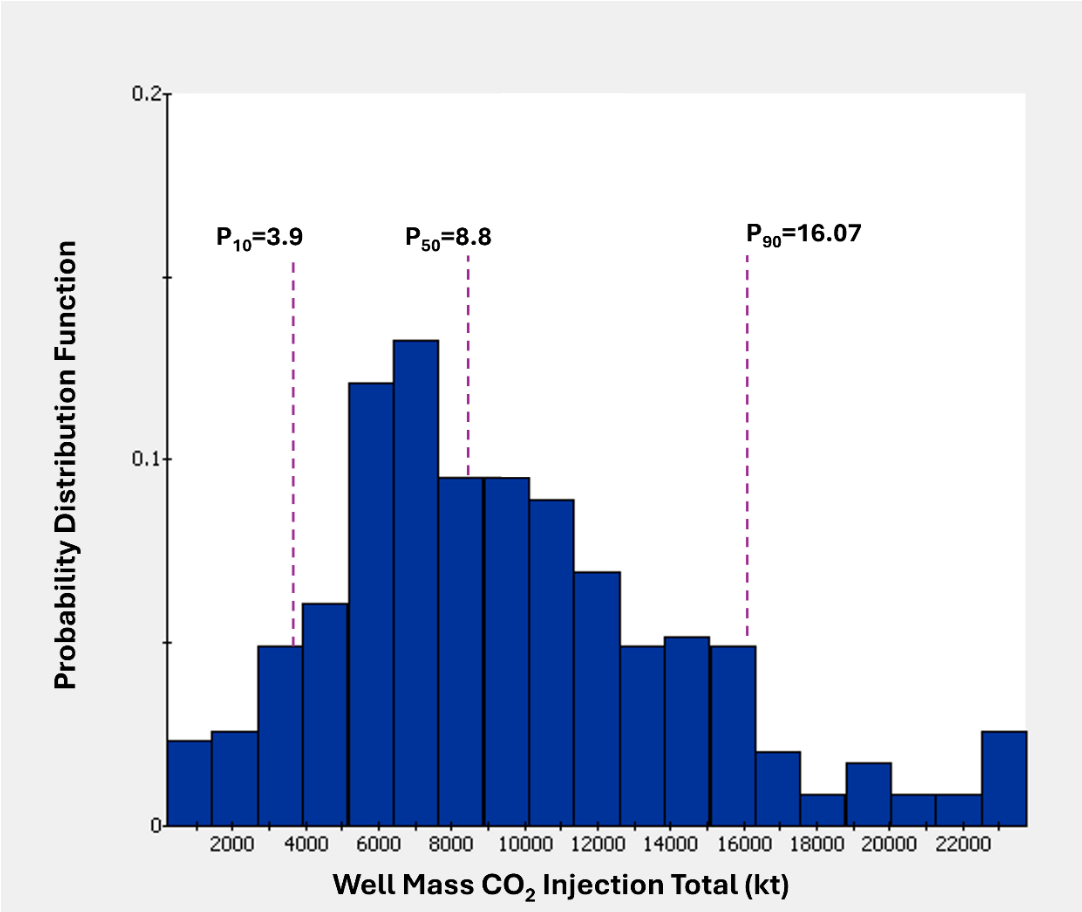

Figure 2 Probabilistic outcomes of CO2 injection modeling showing the Well Mass Injection Total (wmassit) over a 30-year period. Key statistical values include Max: 23.7 million tons, P90: 16.07 million tons, P50: 8.8 million tons, P10: 3.9 million tons, and Min: 0.204 million tons.