Introduction

Carbon capture and storage (CCS) is a key technology for mitigating emissions, requiring efficient transport and injection infrastructure. Offshore CCS projects demand an optimized system design that balances CO_2 storage capacity, safety, and economic feasibility. This study introduces an optimization framework integrating multi-objective optimization (MOO) and dynamic inflow performance relationship (IPR)–outflow performance relationship (OPR) nodal analysis to enhance CCS system design. By systematically analyzing facility specifications and operating conditions, the proposed methodology provides robust decision-making tools for CCS project development.

Methodology

This study applies MOO to determine optimal CO_2 transport and injection parameters, including pipeline diameter, well tubing size, and injection pressures. The Pareto-optimal solutions are refined using dynamic IPR-OPR nodal analysis, which evaluates real-time variations in pressure and temperature. This integrated approach ensures that CO_2 injection remains within operational constraints while maximizing efficiency.

A coupled surface-subsurface simulation is conducted using CMG's CoFlow software to analyze CO_2 flow dynamics. Facility constraints and geological factors are incorporated to develop an adaptable and scalable CCS design. The proposed methodology enables the FEED (Front End Engineering Design) of an integrated offshore CCS system to be developed with higher reliability, enhancing its feasibility and effectiveness.

Results and Discussion

The optimization results define a set of Pareto-optimal solutions, illustrating trade-offs between CO_2 storage capacity, injection safety, and benefit-cost ratio (BCR). Key findings include:

- Increasing CO_2 discharge pressure enhances injectivity but raises the risk of exceeding formation fracture pressure.
- Pipeline diameters influence transport efficiency, with larger diameters reducing pressure drop but increasing infrastructure costs.
- Wellhead temperature affects both phase behavior and hydrate formation, necessitating a balance between energy consumption and flow assurance.
- The optimal operating window ensures stable injection while maintaining pressure within the allowable range to prevent geomechanical instability.

Nodal analysis further refines these insights by incorporating real-time reservoir behavior. The results confirm that, for the specific reservoir model and its associated geological parameters used in this study, an injection pressure range of 9-12 MPa, pipeline diameters of 10-12 inches, and wellhead temperatures of 10-15℃ provide stable and efficient CO_2 injection conditions. This framework enables operators to optimize CCS facility configurations while ensuring that geological and operational constraints are appropriately considered.

Conclusion

This study presents an integrated optimization approach combining MOO and dynamic IPR-OPR nodal analysis for CCS system design. The proposed methodology enhances decision-making by identifying optimal operating conditions and facility specifications. By leveraging advanced simulation techniques, this approach provides a structured framework for improving CO_2 transport and injection efficiency while mitigating operational risks. Future research should extend this framework by incorporating AI-driven predictive modeling and additional geological variability assessments to further refine CCS system optimization. Moreover, validating this methodology through field-scale implementation will provide deeper insights into its practical applicability and scalability for large-scale CCS projects.

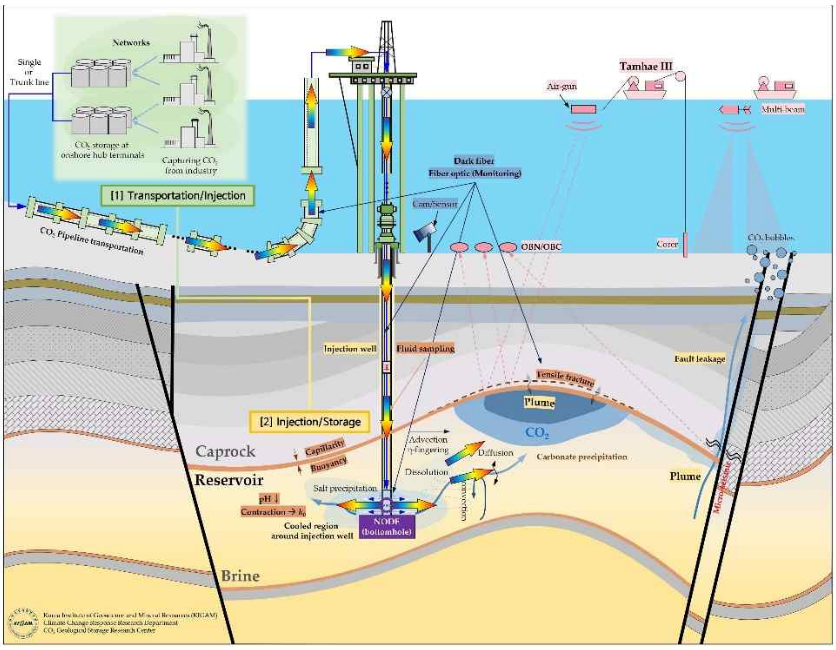

__Figure 1__ Integrated offshore CCS system (Kim et al., 2024).

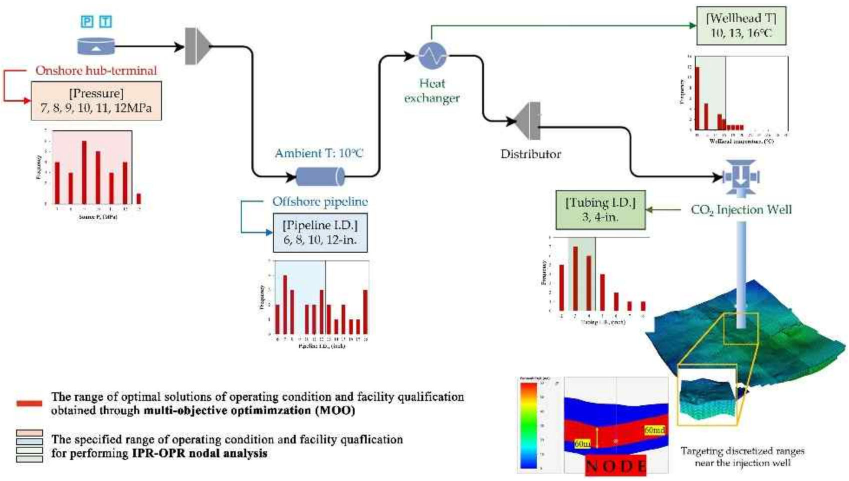

__Figure 2__ Selection of operating conditions and facility qualifications for IPR-OPR nodal analysis and overall concept. The ranges of each decision variables derived from MOO are specified to perform the nodal analysis.

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References

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