

# Streamlining Geophysical Feasibility and Uncertainty Assessment for CCS Monitoring

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## Summary

The proposed workflow integrates flow simulation models with geophysical techniques to assess the feasibility of monitoring CO<sub>2</sub> plume migration and associated risks. It extracts properties like pressure, saturation, and rock attributes for geophysical modeling through flow simulation. The 4D seismic modeling utilizes rock physics and fluid substitution for elastic property estimation, generating seismic responses. CSEM modeling applies Archie's equation to derive resistivity changes from CO<sub>2</sub> saturation for electrical field interpretation, while gravity analysis computes density-based gravitational responses to fluid replacement caused by CO<sub>2</sub> injection. Additionally, the workflow incorporates machine learning to estimate stress-sensitive properties and simulate noise for evaluating detectability under varying conditions.

## Theory / Method / Workflow

The proposed workflow integrates flow simulation models with geophysical techniques to assess the feasibility of monitoring CO<sub>2</sub> plume migration and associated risks. The process begins with extracting properties such as pressure, saturation, and rock attributes from flow simulations. These properties are critical inputs for multi-physics modeling techniques, including:

- **Flow Simulation:** Provides time-variant properties of the subsurface, such as pressure and saturation, essential for modeling geophysical responses.
- **4D Seismic Modeling:** Rock physics and fluid substitution are employed to estimate elastic properties, which are used to generate seismic responses through convolution with a wavelet. This step also incorporates noise simulation to evaluate the detectability of seismic responses under varying conditions.
- **CSEM Modeling:** Resistivity changes are calculated using Archie's equation, enabling the interpretation of electrical fields resulting from CO<sub>2</sub> injection.
- **Gravity Analysis:** Density-based gravitational responses are computed to track fluid replacement caused by CO<sub>2</sub> injection.

Figure 1 illustrates the end-to-end workflow, showcasing the integration of flow simulation with multi-physics modeling techniques. This unified approach ensures consistency across methods while eliminating redundancy. It provides interpretable outputs, including risk maps, which enable users to dynamically generate scenarios and evaluate potential risks associated with CO<sub>2</sub> plume migration.

The workflow also leverages machine learning models to estimate stress-sensitive properties such as bulk and shear moduli from well logs and core data. This ensures an accurate representation of the geomechanical behavior of the reservoir. The result is a holistic and automated solution that enhances the reliability and efficiency of CO<sub>2</sub> monitoring in complex geological settings.

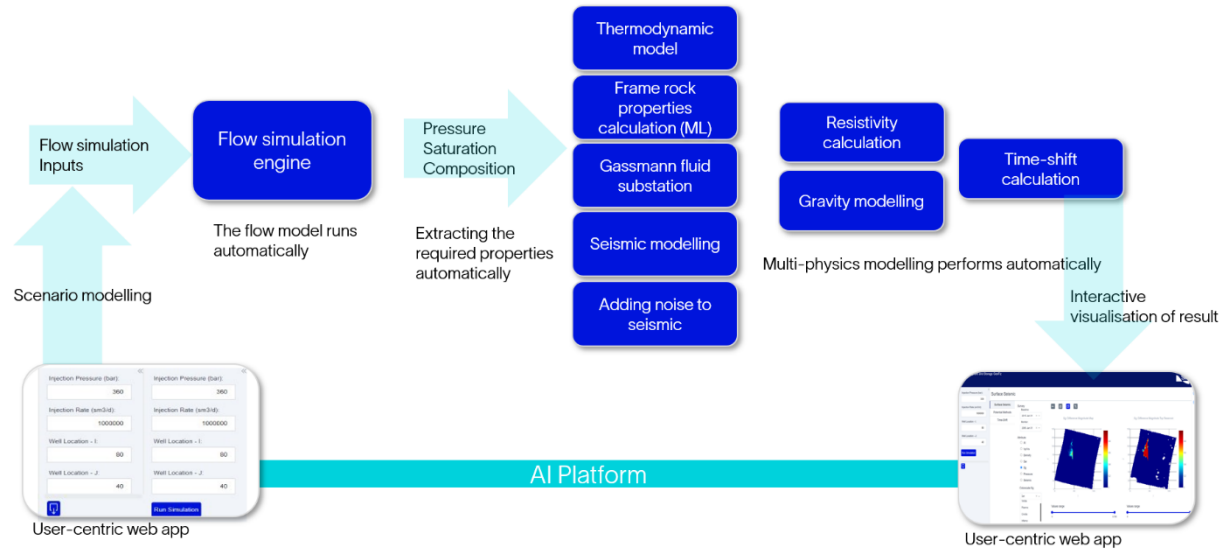


Figure 1: The workflow presented in this paper facilitates an end-to-end solution, which integrates flow simulators and multi-physics modelling. This workflow delivers interpretable results, including risk maps, which enable end users to conduct various scenarios for dynamic result generation.

## Results, Observations, Conclusions

In the Egersund Field case study, the workflow enabled a unified approach to multi-physics modeling, which significantly enhanced the ability to monitor CO<sub>2</sub> plume migration and assess associated risks across critical fault blocks. Key findings include:

- **4D Seismic Monitoring:** The workflow demonstrated that 4D seismic is highly effective for monitoring CO<sub>2</sub> injection at high rates (e.g., 10 million tons per year) even with a normalized root-mean-square (NRMS) noise level of up to 20%. However, at lower injection rates (e.g., 1 million tons per year), the reduced plume size led to diminished detectability, requiring more stringent noise thresholds (NRMS of 10%) to ensure monitoring reliability.
- **Automation and Efficiency:** The automated workflow drastically reduced scenario modeling turnaround times. A process that conventionally required three months was completed in just three minutes, highlighting the efficiency and practicality of the proposed solution.
- **Risk Evaluation:** The automated uncertainty quantification (UQ) workflow enabled dynamic risk assessments, accounting for variations in reservoir pressure over time. By varying key parameters such as porosity, permeability, and fault transmissibility, the workflow provided critical insights into the risk of cap rock failure and CO<sub>2</sub> leakage. A heat map visualization of these risks offered an intuitive understanding of their distribution.

Overall, the workflow presented a dynamic, adaptable, and automated solution for CCS monitoring. It ensures consistency across geophysical techniques, reduces redundancy, and provides a robust platform for scenario analysis, ultimately contributing to the safe and effective implementation of carbon storage projects.

## **Novel/Additive Information**

The proposed workflow introduces a dynamic and automated solution for carbon capture and storage (CCS) monitoring, which significantly enhances the integration of geophysical techniques with flow simulation models. This end-to-end approach eliminates redundancies, ensures consistency, and provides interpretable outputs such as risk maps and scenario-based analyses. Moreover, the automated uncertainty quantification (UQ) workflow is a critical addition, as it dynamically assesses the risks associated with CO<sub>2</sub> injection, such as cap rock failure and leakage, based on variations in reservoir pressure and other parameters. The inclusion of heat map visualizations for risk distribution further enhances its usability, providing stakeholders with a clear understanding of potential risks and mitigation strategies.

This holistic and automated platform represents a significant advancement in geophysical monitoring, offering a scalable and robust solution for addressing the challenges of long-term carbon storage.

## **Acknowledgements**

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## **References**

The Egersund Field simulation model is sourced from the Norwegian Petroleum Directorate (npd.no)- <https://www.npd.no/en/facts/carbon-storage/co2-storage-models-> and is available under the Norwegian License for Public Data (NLOD). License link: <https://data.norge.no/nlod/no/>