Introduction

Monitoring, Measurement, and Verification (MMV) strategies are critical for ensuring the safety, efficiency, and regulatory compliance of Carbon Capture, Utilization, and Storage (CCUS) projects. This study explores advanced MMV techniques, including geophysical monitoring, surface and subsurface technologies, and offshore applications.

This endeavor also examines lessons learned from oil and gas operations, cost-efficient monitoring solutions, and risk mitigation strategies for leakage and seismicity. The research aims to provide a fit-for-purpose framework for reliable and scalable CCUS monitoring.

Method and/or Theory

This study evaluates MMV methodologies used in CCUS, integrating geophysical, well-based, and offshore monitoring techniques. Seismic imaging, electromagnetic surveys, and fiber-optic sensing are analyzed for their ability to track CO_2 plume migration and detect anomalies. Subsurface monitoring methods, including downhole pressure and temperature sensors, are assessed for well integrity and containment assurance.

Then, offshore technologies, such as seabed monitoring stations and satellite-based remote sensing, are explored for deepwater CO_2 storage applications. Additionally, cost-effective MMV solutions derived from oil and gas field tests are examined, emphasizing risk assessment, leakage detection, and mitigation strategies for natural and induced seismicity.

Conclusions

The study highlights the effectiveness of integrated MMV strategies in ensuring long-term CCUS integrity. Geophysical techniques, such as time-lapse seismic monitoring and distributed acoustic sensing (DAS), have demonstrated high-resolution tracking of CO_2 migration in storage reservoirs.

Subsurface well-based monitoring using pressure sensors and microseismic networks provides real-time data for early leakage detection and reservoir performance evaluation. Offshore CCUS projects benefit from ocean-bottom seismic monitoring and remote sensing technologies, offering scalable solutions for deepwater carbon storage.

Lessons from the oil and gas industry emphasize the importance of multi-technology integration for cost-efficient and fit-for-purpose MMV. Adaptive monitoring strategies, combining real-time data analytics with AI-driven anomaly detection, enhance operational decision-making while reducing monitoring expenses. However, challenges remain in addressing seismicity risks associated with CO_2 injection, requiring further research on induced seismicity mitigation and reservoir pressure management.

This study underscores the need for standardized MMV frameworks, combining advanced monitoring tools and risk assessment protocols, to ensure the long-term success of CCUS projects.

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