An Integrated Workflow for CCS Characterization, Geomechanics, Dynamic Modelling, and Model-Driven Monitoring

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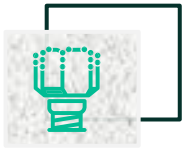
CO_2 sequestration: from screening to project execution

SITE SCREENING	SITE CHARACTERIZATION	SITE DEVELOPMENT	SITE OPERATIONS	SITE STEWARDSHIP
Data review leading to site screening and selection	**Analytics and modelling to permit application**	**Site construction and service mobilization**	**Initiate injection and monitoring**	**Complete injection and initiate closure**
				
Pre-FEED and FEED assessment Site selection **Containment risk register** Storage capacity potential	Area of Review (AoR) determination Subsurface modelling & interpretation Pilot well construction Coring, CH & OH logging **Develop site monitoring plan (MMV)** Establish injection rates and baselines Permit application	Well basis of design Integrated well construction Multi-stage completion designs Operational and field procedures **MMV planning** **Permanent monitoring solutions** **Digital platform calibration & readiness**	**Integrated well & MMV services** **Digital platform deployment** Field Operations Realtime monitoring Seismic acquisition & interpretation Analytics & model updates Site maintenance planning **Regulatory reporting**	**Post-Injection Site Care (PISC)** Intervention (if needed) **Long-term monitoring solutions** Abandonment & decommissioning Permitting & maintenance

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Why Integrated Assurance Matters

The Challenge

Many CCS projects develop subsurface characterization, geomechanics, reservoir simulation, monitoring, and verification activities in parallel, but these workstreams often remain only partially connected.

As a result:

- Monitoring programs are designed without a direct link to key storage risks.
- Geomechanical and containment risks are not continuously updated as new monitoring data becomes available.
- Predicted reservoir behaviour and observed field performance diverge over time.
- Verification and regulatory reporting become reactive rather than predictive.
- Project teams struggle to demonstrate long-term storage integrity and containment assurance with confidence.

Consequences of Fragmented Workflows

Challenge	Impact
Disconnected models and datasets	Increased uncertainty
Generic MMV programs	Higher monitoring costs
Limited integration of monitoring data	Delayed detection of anomalies
Manual reporting processes	Increased regulatory burden
Separate technical workstreams	Reduced confidence in storage performance

Integrated CCS Assurance transforms monitoring from a compliance activity into a **risk-informed decision-making tool**, improving storage confidence, reducing uncertainty, and supporting successful long-term CO_2 containment

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Risk Driven MMV Design

Monitoring is tailored to specific risk and decision needs

Risk	Monitoring Objective	Example Technology
Caprock breach / Containment failure	Detect pressure anomalies and caprock leakage	Pressure gauges, DAS, 4D seismic, geochemistry
Fault Reactivation / induced seismicity	Detect deformation and seismic events	Microseismic, DAS, geomechanics
Plume migration outside target zone	Track plume extent and migration pathways	4D seismic, EM, geomechanics
Legacy well leakage	Detect leakage through abandoned well	Fiber optic, pressure, soil and gas monitoring, tracer
Injectivity / Conformance Issuses	Monitor injectivity and conformance	Pressure, temperature, PLT, DAS

Why Risk Driven?

- Focus monitoring investment where it matters most
- Optimize cost by avoiding unnecessary data
- Enable timely decision and response
- Strengthen regulatory confidence and demonstrate due diligence

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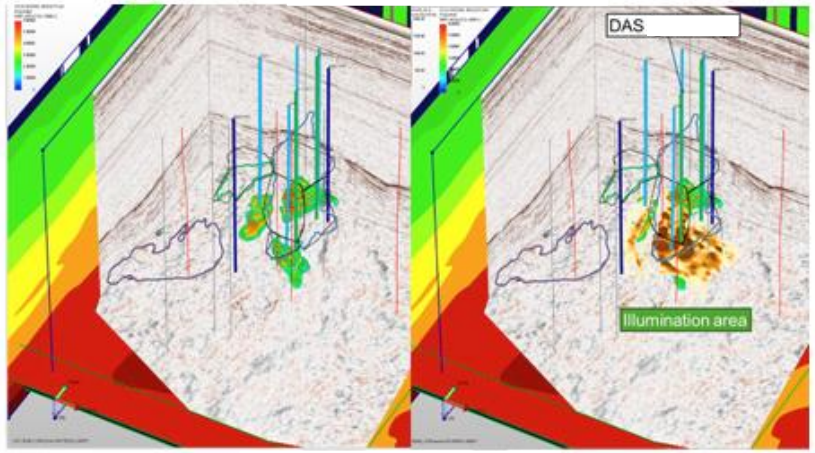
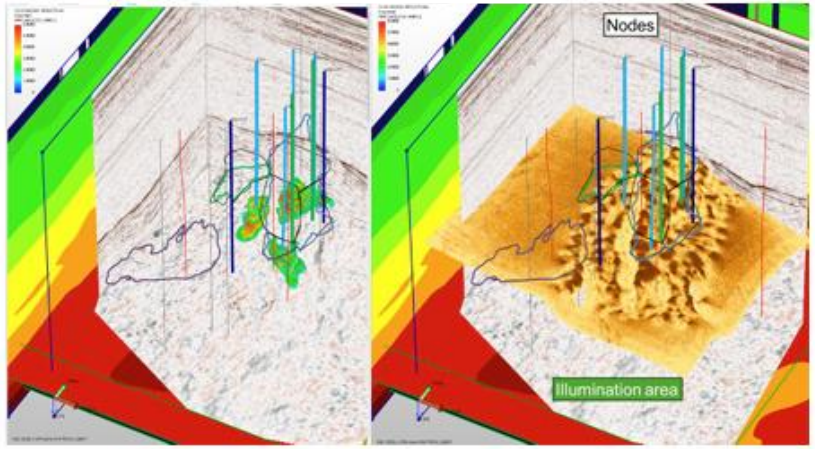
Rock physics and Monitoring Feasibility

Evaluate detectability before field deployment to optimize MMV

DAS Illumination

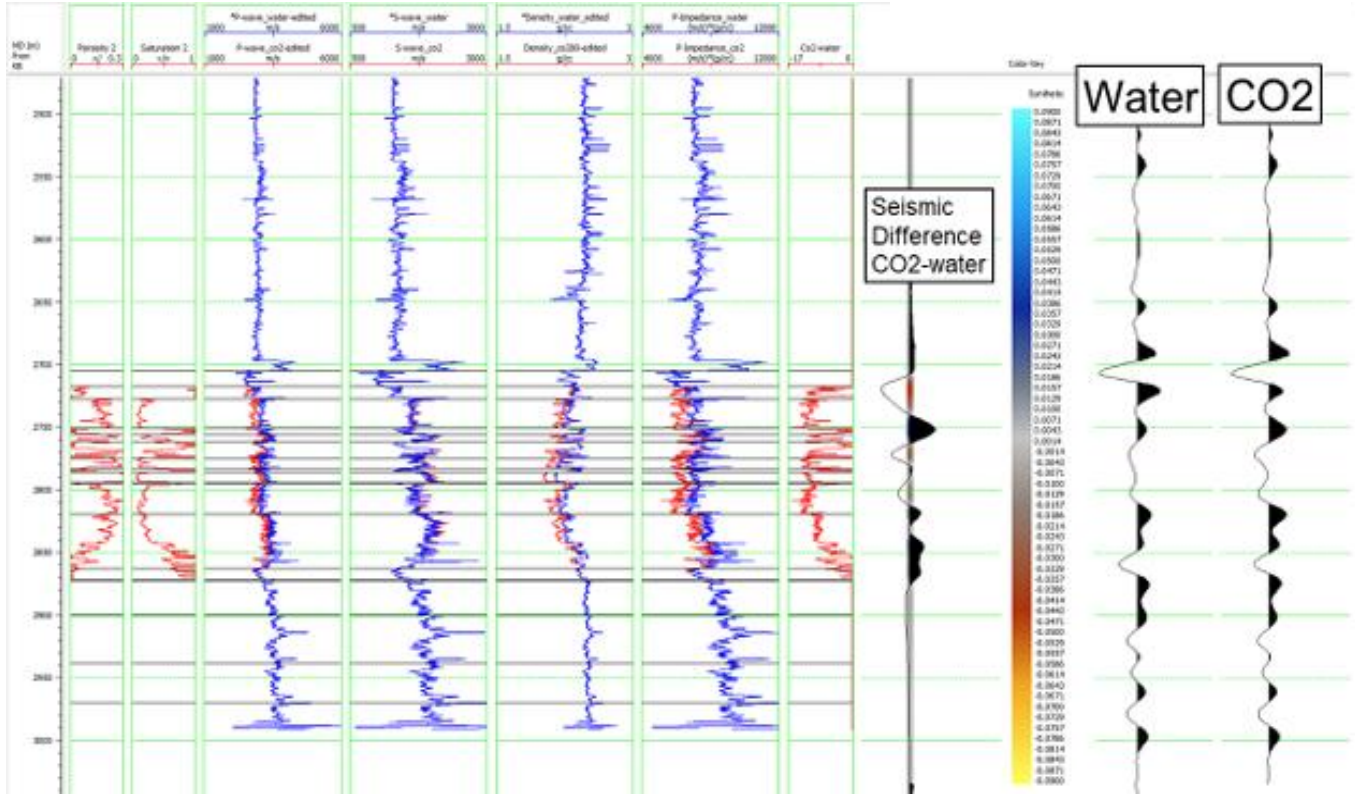


Node Illumination



Not limited to:

- Assessing expected effect of CO_2 on velocity / 4D seismic
- Identifying alternative method to monitor plume migration



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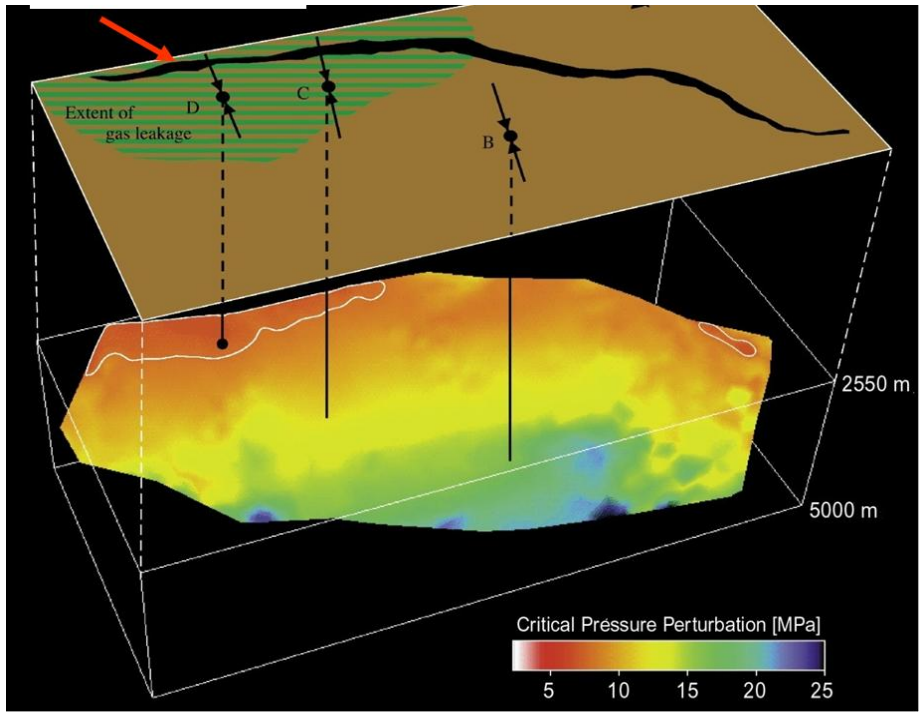
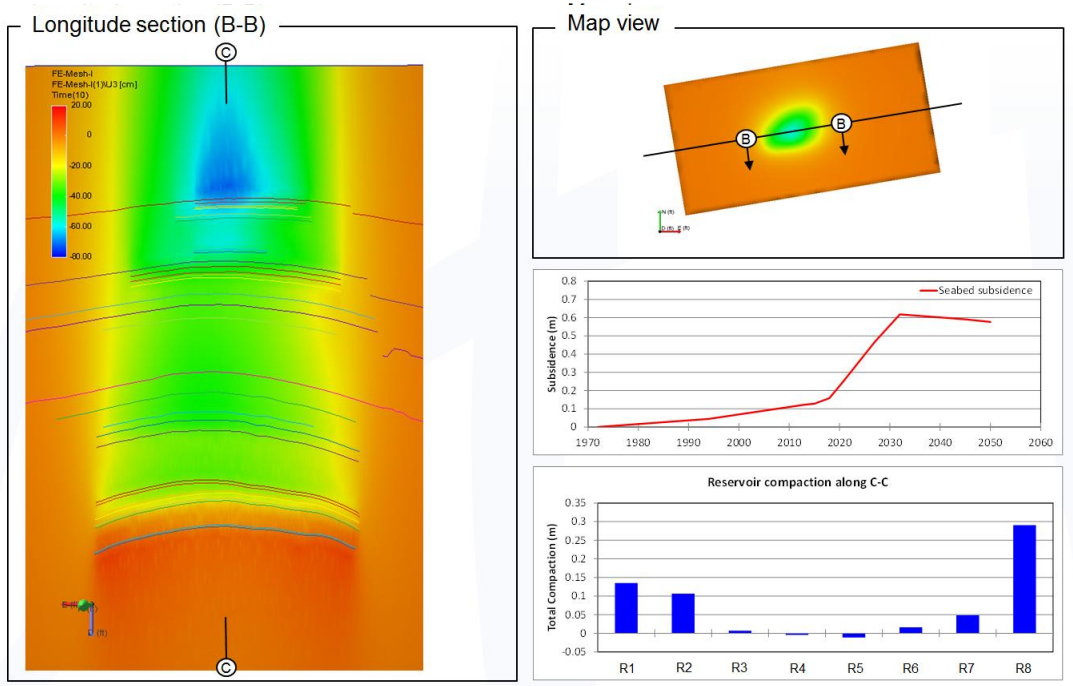
Role of geomechanics in CCS Assurance

1D Geomechanics | 3D Dynamic Coupled Geomechanics | **4D Geomechanics** | Fault Stability Analysis | Compaction & Seabed heave | Thermal Fracturing | Seismic Risk Analysis





Ensure storage integrity and containment

Quantify risk and reduce uncertainty

Support injection operations and optimization

Enable confident decision-making and regulatory compliance

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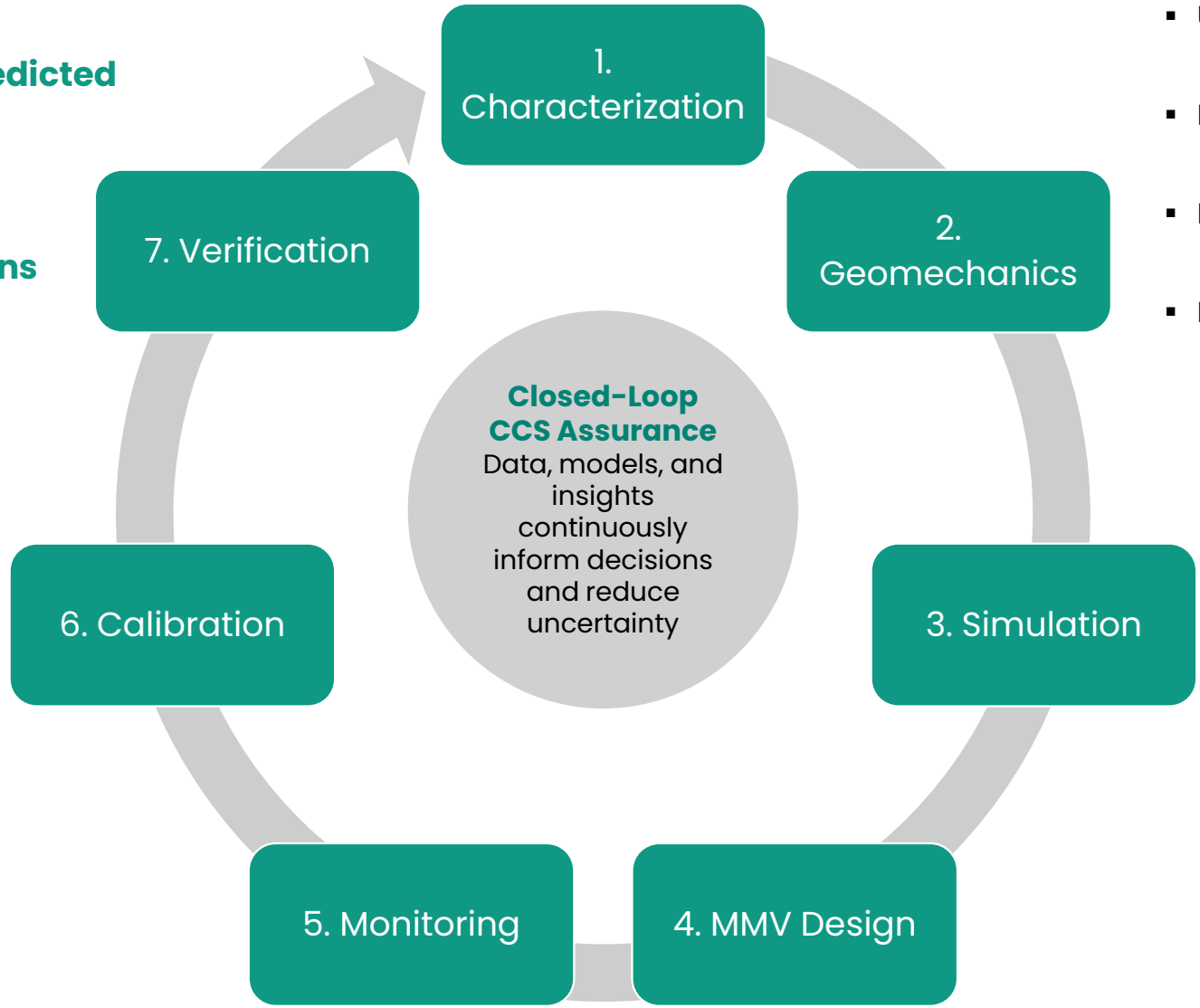
Verification & Model Calibration Loop

Better match between predicted and observed behavior
- Improved model reliability

Early detection of deviations and anomalies
- Enable timely response

Adaptive monitoring optimization
- Focus on what matters

Defensible technical basis for decisions and reporting
- Support regulatory confidence



Outputs

- Updated forecast and scenarios
- Reduced uncertainty
- Improved assurance
- Regulatory confidence

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CarbonEdge™ MMV solutions

Enabling the Digital Backbone of the CCS Assurance

Connect

Single pane of glass to the entire CCUS value chain

- Integrated asset model
- Connecting sub-surface to surface
- Visualization of data from sensors and sources

Mitigate

Identify and mitigate project risks

- Implementation of risk catalog & risk register
- Customizable alarms based on sensor data
- Advanced analytics to detect anomalies

Optimize

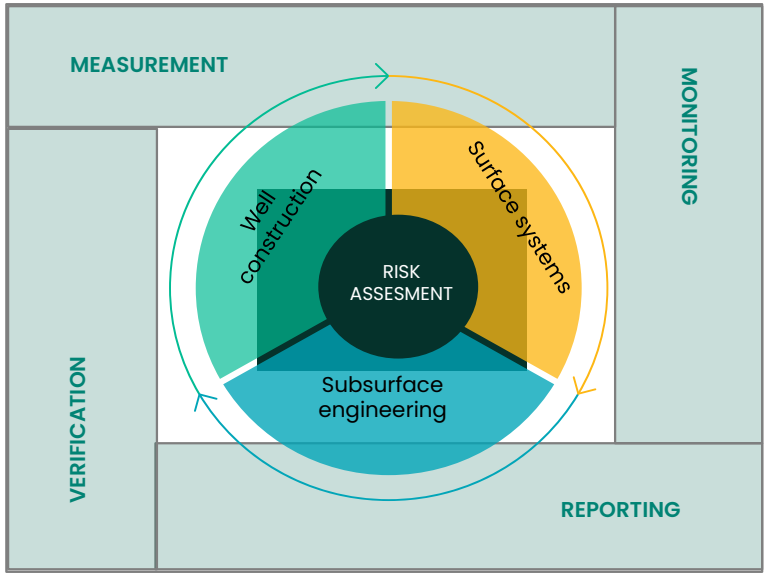
Improve Operational Efficiency

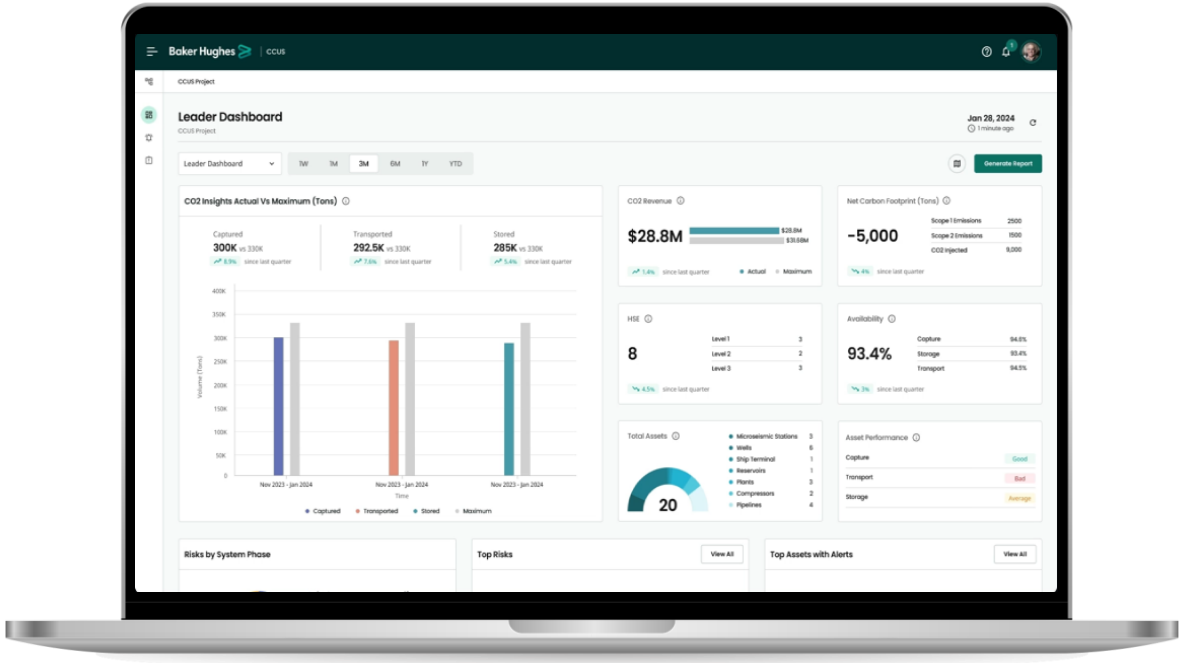
- Reduction of non-productive time
- Proactive preventive measurements insights
- Continuous process optimization along lifecycle

Report

Simplify and expedite reporting

- Enabling compliance and regulatory reporting
- CO2 accounting for multi tenant assets





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Benefits of Model-Driven Monitoring

Technical Benefits

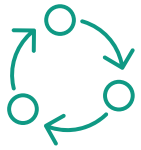
- Reduced uncertainty in plume migration forecast
- Improved pressure history matching
- Earlier anomaly detection
- Better containment assurance
- Optimized MMV deployment

Operational Benefits

- Reduced monitoring cost
- Faster permitting support
- Improved regulatory confidence
- Reduced false alarms
- Adaptive monitoring

Quantified Impact

Reduced Uncertainty
20–35% improvement in plume extent forecasting



Improved Calibration
30–50% reduction in pressure and plume mismatch

Faster Permitting
Shorter preparation time while maintaining risk rigor

Model-driven monitoring turns data into actionable insights, reducing uncertainty and improving confidence in long-term CO2 storage performance

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Key Takeaways

An integrated workflow ensures that:

- Integrated workflows connect characterization, geomechanics, simulation, MMV and verification across the full CCS lifecycle.
- Monitoring objectives are explicitly linked to identified risks and performance criteria.
- Model-driven monitoring with closed-loop calibration reduces uncertainty and improves prediction reliability
- Uncertainty is progressively reduced throughout the project lifecycle.
- Storage performance, containment, and conformance can be demonstrated with greater confidence.
- Regulatory reporting is supported by a transparent and auditable technical framework.
- Advanced technologies (4D seismic, Sparse Nodal Seismic, DAS, fiber optic, microseismic, etc.) are optimally selected and deployed

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