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Carbon Storage Technology and Monitoring Strategies for Malaysia: a Review

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Rising global temperatures and intensifying climate extremes in 2024, as reported by the World Meteorological Organisation, underscore the urgent need for effective carbon management solutions. Carbon capture and storage (CCS) is a strategic technology for meeting the net zero carbon emission target of Malaysia by 2050. This study reviews the technical readiness and monitoring strategies of leading CCS projects worldwide, including Sleipner (Norway), Quest (Canada) and Aquistore (Canada), with a particular focus on site characterisation, injection operations and long-term containment monitoring. By analysing these global case studies, the paper identifies key insights into measurement, monitoring and verification (MMV) systems such as seismic imaging, distributed acoustic sensing and pressure tomography that are essential for secure and effective CO_2 storage. The review highlights both challenges and successes across a range of geological storage sites, emphasising the need for advanced predictive modelling techniques and the development of standardised regulatory frameworks to ensure long term storage security. These lessons provide a foundation for strengthening carbon storage capabilities in Malaysia, particularly at offshore sites which are progressing towards operational readiness. The paper concludes that further integration of advanced monitoring technologies and comprehensive predictive modelling is critical to reinforce long-term containment assurance. Adoption of comprehensive, end-to-end carbon storage processes aligned with international best practices will enhance stakeholder confidence. These strategies will support a substantial transition to a low carbon energy system and contribute significantly to achieving net zero carbon emissions by 2050.

1. Introduction

The World Meteorological Organisation (WMO) reported 2024 as the warmest year on record, with a global temperature anomaly of 1.54°C higher than pre-industrial levels due to accelerating climate extremes. The International Energy Agency (IEA) noted surging electricity demand driven by cooling needs during 2024 heatwaves. In Southeast Asia, the abundance of fossil fuel resources creates an urgent need for reliable carbon storage solutions to meet net-zero emissions targets (Sukor et al., 2020). In Malaysia, electricity generation reached 15.32 TWh by September 2025, with a 1.59% growth; coal (45%) and gas (33%) dominate the energy mix, while low-carbon sources contribute just over 20% (Ember, 2025). The country faces a pressing need to reduce reliance on fossil fuels, as the energy sector accounts for nearly 80% of greenhouse gas emissions (MGTC, 2023). To support Malaysia's 45% emissions intensity reduction target by 2030 and net-zero goal by 2050, Carbon Capture, Utilisation, and Storage (CCUS) has become an essential technology. However, high costs and limited investor interest remain barriers, necessitating government incentives such as tax credits and financial support to advance practical CCUS deployment (Thepsaskul et al., 2023).

Malaysia is committed to achieving net-zero emissions by 2050, positioning CCS as a core decarbonisation strategy under the 13th Malaysia Plan and the National Energy Transition Roadmap. The roadmap includes six key transition levers such as CCS, Hydrogen, Energy Efficiency, Renewable Energy, Bioenergy and Green Mobility, structured into ten flagship projects. These initiatives target a significant reduction in emissions, expected to cut greenhouse gases by over 10 Mt CO_2/y CO_2 and attract substantial investments exceeding RM25 billion. Malaysia readiness is reinforced through the forthcoming CCS Bill, which provides a dedicated legal framework for storage operations, and the establishment of the Malaysia CCUS Agency (MyCCUS) to

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oversee licensing, compliance, and monitoring. A concise review was conducted encompassing peer-reviewed articles, technical project reports, and regulatory documents published between 2015 and 2025. The focus was on carbon storage and measurement, monitoring, and verification (MMV) technologies relevant to Malaysia and comparable regional contexts. Sources were carefully selected based on their emphasis on technology deployment, regulatory compliance, field case studies, and availability as open-access materials. The key findings were synthesised and reviewed with the objective of informing the adoption of monitoring strategies in Malaysia to ensure long-term storage integrity and compliance with international best practices.

Effective MMV technologies are critical for successful CCS deployment, reducing risks of delays, inefficient capital use, and environmental or regulatory issues caused by uncertainties in storage containment. MMV enables early detection of CO_2 leakage, ensuring long-term storage safety and compliance with international standards. By consolidating technical monitoring acumens, this review provides actionable insights for effective CCS deployment in Malaysia, directly supporting the 2030 emissions reduction target and the 2050 net-zero goal.

2. Geological Storage and MMV

The integrity of the storage site is central to the success of CCS, with the strength of the host rock controlling plume migration and long-term containment. Suitable geological formations include depleted oil and gas reservoirs, coalbed methane reservoirs, basalt, and deep saline aquifers, each offering distinct storage capacities and challenges. Saline aquifers are often preferred due to their wide distribution, ability to dissipate injection pressure, and reduced risk of caprock failure when fracture pressures are low (Jung and Lee, 2024). Assessing storage security requires comprehensive reservoir and seal characterisation using seismic surveys, core analysis, and formation evaluation to determine capacity and integrity. In depleted reservoirs, CO_2 is primarily retained through structural and stratigraphic trapping beneath impermeable caprocks, supported by geochemical dissolution in formation fluids. Coalbed methane reservoirs additionally provide adsorptive trapping where CO_2 replaces methane, offering enhanced methane recovery alongside storage (Zhang et al., 2022). Advanced MMV methods are required integrating surface and subsurface monitoring, such as InSAR combined with UAV 3D surface modelling, have successfully visualized CO_2 migration and surface deformation, improving understanding of reservoir dynamics and faults (Zhang et al., 2022). Geomechanical modelling assesses fault reactivation and seal failure risks under injection pressures, with studies confirming structural integrity in offshore Sarawak (Chiaramonte et al., 2024). Sensitivity analyses incorporating local stress, fault properties, and reservoir heterogeneity help optimize injection strategies and mitigate leakage and seismicity risks (Chiaramonte et al., 2024). MMV programs ensure secure containment by conducting baseline site characterization through seismic and logging surveys (Rostron et al., 2014), verifying plume migration and reservoir performance during injection (Harvey et al., 2022), and implementing adaptive post-injection monitoring to maintain integrity and environmental safety (Gasperikova et al., 2022). Table 1 summarises key international carbon storage sites with monitoring, measurement and verification (MMV) programmes, highlighting lessons for injection operations and including the Kasawari project capacity. The integration of multi-scale monitoring approaches is vital to establishing safe, verifiable, and sustainable geological CO_2 storage.

Beyond Kasawari, the Sarawak Basin total storage potential is estimated in the gigatonne range, supporting Malaysia's ambition to develop multiple CCS hubs with combined capacities exceeding 15 Mtpa by 2030 (Hasbollah and Junin, 2017). In the 2024 Comprehensive CCUS Research Report, the GCCSI and ERIA note that ASEAN countries vary substantially in CO_2 storage capacity; for example, Indonesia South Sumatra Basin offers limited storage around 5.6 $MtCO_2$ in smaller oil fields, which highlights Malaysia comparative strategic advantage. MMV programs have been widely implemented by oil and gas companies to ensure that CO_2 storage sites comply with environmental and regulatory requirements. To maintain international credibility and guarantee safe, secure storage operations, it is recommended that recognised standards such as ISO 27914 and DNV RP J203 be adopted across all stages of the CCS process, from site selection through to post-closure surveillance. Effective geological CO_2 storage requires a comprehensive strategy that integrates detailed reservoir characterisation, thorough geomechanical risk assessment and multi-scale monitoring, measurement and verification. The use of diverse technologies including seismic surveys, InSAR, UAV imaging and pressure monitoring is essential for early detection of potential leakage or fault reactivation, particularly in complex and compartmentalised reservoirs. Continuous adherence to international standards combined with adaptive management throughout the storage lifecycle is critical to ensuring long-term containment integrity and environmental safety. These geological and monitoring requirements directly influence the design of injection infrastructure and the selection of appropriate technologies. The following sections examine how conformance monitoring supports reservoir performance during injection (Section 3) and how containment monitoring safeguards long-term storage integrity (Section 4).

Table 1: Storage Sites and MMV

Storage Site	Storage Details and MMV
Quest Site, Canada (Freeman et al., 2024)	Injects ≈ 1.1 Mt CO_2/y since 2015 into a deep saline aquifer at ~2 km depth. Demonstrated secure long-term storage.
Sleipner Site, Norway (Tangedal, 2024)	Operating since 1996, injecting ≈ 1 Mt CO_2/y into saline aquifers. CO_2 plume rises, trapped under caprock, expands laterally forming stable saturated zones under shale layers. Questions remain on long-term caprock sealing.
Aquistore Site, Canada (Sacuta and Movahedzadeh, 2024)	Injection started 2015 into permeable sandstone, capacity up to 0.6 Mt CO_2/y. Comprehensive characterisation supports MMV and risk assessments. New monitoring wells deployed to study CO_2 saturation effects, rock-fluid interactions, seismic data acquisition, and implement new MMV technologies.
Snøhvit Site, Norway (Chiaramonte et al., 2024)	Operated by Equinor; injects ≈ 1 Mt CO_2/y since 2008 from LNG production into deep saline aquifer. MMV includes pressure monitoring, seismic surveys, injection optimisation. Pressure buildup risk in compartmentalized & faulted reservoir highlights need for early pressure change detection to prevent fault reactivation, leakage, and induced seismicity.
Kasawari CCS & Sarawak Basin, Malaysia (Global CCS Institute (GCCSI) & Economic Research Institute for ASEAN and East Asia (ERIA), 2024)	Targets 3.3–3.7 Mt CO_2/y injection/storage contributing to Malaysia's carbon strategy. Sarawak Basin storage potential in Gt scale, enabling multiple CCS hubs with combined >15 Mt/y capacity by 2030.

3. Infrastructure and Conformance Monitoring Technologies for CO_2 Injection

Conformance monitoring is essential for tracking the movement of the CO_2 plume, managing injection operations to guide its flow, and validating its behaviour against predictions from reservoir modelling. Injection systems require expert operators to evaluate geological conditions and assess the integrity of the storage site to prevent carbon leakage (Majhour and Faroughi, 2023). Key infrastructure components such as pipelines, well design, pressure management, and operational controls must be carefully managed during CO_2 injection to ensure the security of infrastructure, safety of personnel, and protection of the environment.

Chemical interactions between CO_2 and subsurface fluids, such as formation water, can create acidic conditions that react with minerals, causing dissolution or precipitation and producing residual chemicals that accelerate corrosion. Therefore, infrastructure and well design must consider the corrosive and buoyant nature of CO_2. This includes assessing legacy wells, validating cement placement, evaluating casing integrity, conducting periodic wellbore monitoring (including near-wellbore regions), and developing remediation strategies (Valstar et al., 2024). Whether drilling new wells or repurposing existing oil and gas wells, thorough evaluation of material and operational risks is essential to mitigate well integrity issues during injection. Casing and operational failures remain key concerns requiring proactive management. Specialised risk management is necessary because CO_2 blowouts differ from hydrocarbon blowouts. CO_2 rapidly forms hydrates under cold, high-pressure conditions when mixed with reservoir brine and seawater, posing unique well control challenges. Zhou et al. (2024) highlighted that although containment risks exist through microfracture networks, installing sensors combined with comprehensive operational monitoring enables early detection of equipment failure. Risk analysis tools can predict device failure, while reservoir simulations forecast potential leakage, enhancing preparedness. The injection phase of CO_2 storage presents significant technical and operational challenges that require careful planning and ongoing monitoring. Advanced monitoring technologies and real-time data collection enable early detection of issues and timely responses. Additionally, specialised operational strategies are needed to address chemical interactions and risks such as hydrate formation. Figure 1 summarises the key infrastructure during CO_2 injection, categorised into material selection, well design, injection modelling, fibre-optic sensing and real-time seismic monitoring.

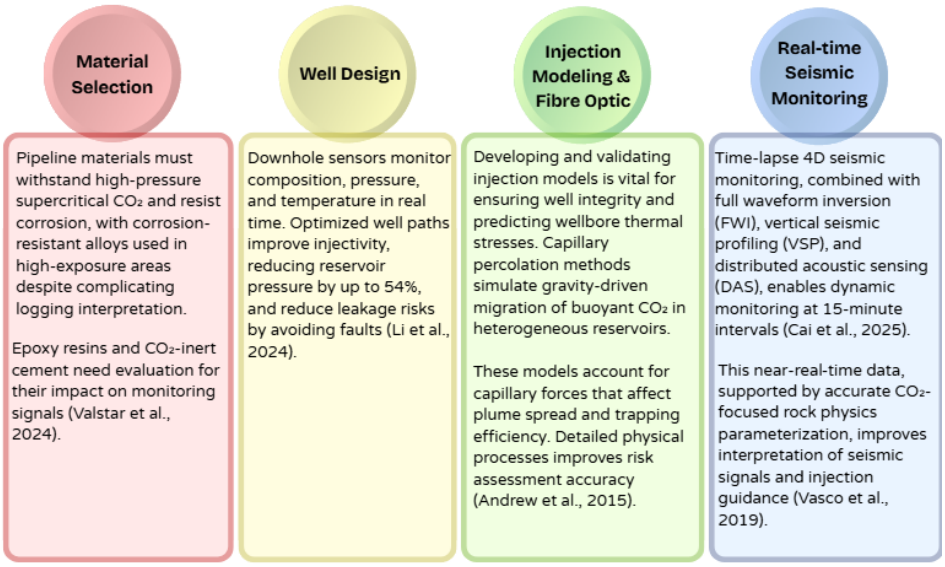

Figure 1: Overview of key infrastructure for injection monitoring from recent expert studies

Maintaining the integrity of legacy wells and wellbores prevents potential leakage. Continuous evaluation of cement placement, casing condition, and wellbore health, along with precise modeling of fluid migration and thermal stresses, enhances injection safety. Overall, a comprehensive approach combining infrastructure integrity, monitoring, and predictive modelling is essential to ensure secure and effective CO_2 storage. Proactive management of well integrity, especially for legacy wells, alongside the integration of advanced sensing and modelling tools, reduces leakage risks and supports sound decision-making, contributing to the long-term success and sustainability of carbon storage projects.

4. Long-term CO_2 Containment Monitoring Technologies

Monitoring the integrity of CO_2 storage sites and caprock sealing is essential to ensure permanent containment and environmental safety. A multi-layered approach combining surface and subsurface techniques provides comprehensive site security. Subsurface monitoring leverages tools such as Distributed Acoustic Sensing (DAS), pressure sensors above the caprock, groundwater sampling, and geochemical tracers, integrated with seismic data to improve early leak detection and operational decision-making (Ringrose and Meckel, 2019). Time-lapse 4D seismic monitoring plays a central role by offering deep penetration, high spatial resolution, and reliable estimates of reservoir dynamic properties, reducing uncertainties in simulation models (Rezaei et al., 2020). Long-term monitoring utilizes 4D seismic integrated with geomechanical and fluid flow models to track CO_2 plume migration and reservoir responses such as pressure changes, subsidence, and compaction (Sambo et al., 2024). Complementary techniques including vertical seismic profiling and microseismic monitoring provide critical insights into fracture dynamics and subtle geomechanical changes, enhancing detection of potential leakage pathways. The Quest CCS project in Canada exemplifies the effectiveness of these integrated technologies in confirming permanent CO_2 storage. Continuous advancement and integration of multi-method monitoring remain vital to maintaining sensitivity, spatial coverage, regulatory compliance, and public confidence in carbon capture and storage. Surface-based non-invasive methods like soil-gas flux chambers, InSAR, and GPS detect ground movement and surface emissions, enabling prompt intervention when anomalies arise.
InSAR monitoring has been successfully applied at multiple global CCS sites, including In Salah (Algeria), Sleipner (Norway), and Ketzin (Germany) (Vasco et al., 2019) including in Gulf Coast. Zhang et al. (2022) stated that the resolution of spaceborne data is low and needs to be improved for areas with vegetation for onshore storage sites. InSAR provides wide-area, cost-effective surface deformation monitoring for CCS but faces challenges from vegetation interference and limited spatial resolution. Injection of 3 million tons of CO_2 causes measurable surface deformation of a few millimeters per year, with InSAR data showing preferential CO_2 flow away from injection wells (Vasco et al., 2010). Figure 2 shows the containment monitoring technologies that are vital for real-time and prompt detection of anomalies. The technology revealed that the CO_2 flow creates a tensile feature at reservoir depth that aligns with a seismically detected fault, highlighting geological control on CO_2 migration. UAV offers flexible, high-resolution 3D monitoring with diverse sensors, bridging satellite and ground methods for real-time leak and deformation detection (Zhang et al., 2022).

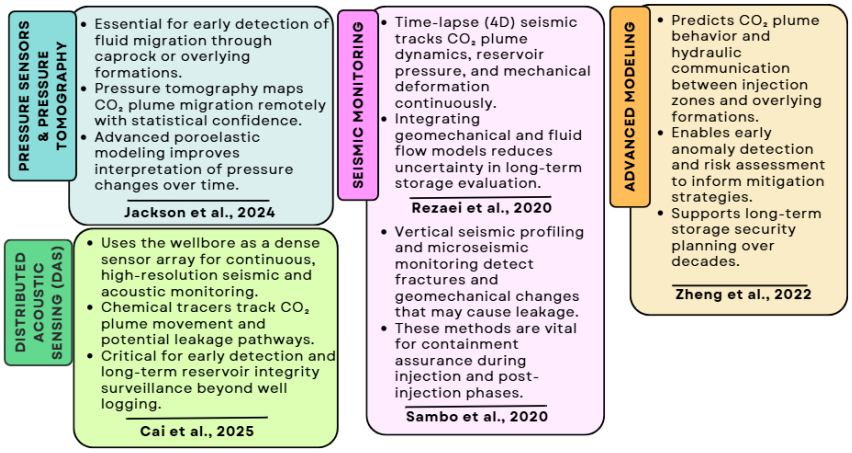

Figure 2: Summary of recent technologies for containment monitoring

Surface and subsurface monitoring are essential for ensuring the safety and security of CO_2 storage. These two modes of observation, one above ground and the other subsurface, provide comprehensive verification of containment and enable early detection of any anomalies that could indicate leakage or caprock failure. Combining InSAR, UAV, and seismic data enables accurate, multi-method 3D monitoring essential for ensuring long-term CCS safety and effectiveness.

5. Conclusion

As the energy transition accelerates, collaboration among government, industry, and researchers is critical to meeting long-term climate goals. Geological CO_2 storage is central to Malaysia's 2050 net-zero pathway, underpinned by the CCUS Bill 2025, offshore hub development, and a strengthening regulatory framework. Safe deployment requires credible site characterisation, well integrity, and long-term MMV strategies that combine conformance monitoring to validate plume behaviour with containment monitoring to assure permanent storage security. To accelerate readiness, industry should prioritise investment in injection–containment modelling and site-specific monitoring, while policymakers need to establish a phased national CCS roadmap, introduce targeted incentives, and mandate independent storage audits. At the same time, researchers should advance cost-effective monitoring tools tailored to Malaysia's geology and enhance data integration for early risk detection. Coordinated action across these fronts will position Malaysia as a regional leader in safe and effective CO_2 storage.

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