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Review

Monitoring Technology Systems for CO_2 Geological Storage: Comparison of Typical International CCS Projects and the Shenhua CCS Demonstration Project

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Abstract

Carbon capture and storage (CCS) is a key backstop technology for achieving carbon peaking and carbon neutrality, and a monitoring system that is safe, effective and cost-rational is a prerequisite for the approval, continued operation, and public acceptance of CO_2 geological storage projects. This paper reviews the monitoring technology systems of ten typical international CCS projects—Sleipner, Northern Lights, Tomakomai, In Salah, Decatur/IBDP, Nagaoka, Weyburn–Midale, Cranfield, Otway, and Ketzin—and analyzes how four factors—storage type, geological conditions, regulatory context, and project stage—shape the technical route of monitoring. China's first full-chain saline-aquifer storage demonstration, the Shenhua Ordos CCS project, is then compared with these projects along multiple dimensions. The results show that mature international projects generally adopt risk-driven, full-lifecycle, and hierarchically designed monitoring programs: offshore saline-aquifer projects rely on time-lapse (4D) seismic as the core method, supplemented by gravity, electromagnetic, and marine environmental monitoring, whereas onshore projects have developed site-specific combinations such as InSAR, permanent electrical resistivity, microseismic, and integrated VSP. For Shenhua CCS, three time-lapse VSP surveys formed the core of its geophysical program (the plume migration range within the injection interval extended from 350 m to 450 m, with no wave-field anomaly detected in the caprock at about 950 m depth), supplemented by self-developed downhole pressure/temperature gauges (drift error reduced from 2.17% to 0.26%) and multi-indicator near-surface monitoring; within an injected volume of 302,600 t, no leakage was detected in any monitored domain at the sensitivity of the deployed arrays, with a construction capital expenditure of about RMB 210 million (≈USD 31 million) and a full-chain cost of about RMB 280/t (≈USD 41/t). Compared with advanced international practice, gaps remain in the design paradigm (the transition from verification-oriented to risk-oriented design has not yet been completed), the large-scale application of high-resolution geophysics, institutionalized monitoring–modeling closure and data sharing, and technical standards and equipment localization. A pathway of risk-based hierarchical design, low-cost high-value technology portfolios, monitoring – modeling closure, standards first, and data sharing is therefore proposed for China's megaton-scale storage projects.

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1. Introduction

1.1. Background and Necessity of Monitoring

In 2020, China set the strategic goals of peaking carbon emissions before 2030 and achieving carbon neutrality before 2060. CO_2 geological storage, as a key technological pathway for large-scale CO_2 emission reduction and for net-zero emissions from fossil energy, is moving from demonstration towards large-scale deployment [1,2]. However, CO_2 may escape through caprock pore systems, faults and fracture channels, wellbores, and hydrological systems under natural and anthropogenic influences [3]. Once leakage occurs, it may cause acidification of shallow groundwater and mobilization of heavy metals, disturbance of soil ecosystems, damage to vegetation and crops, and human safety risks arising from locally elevated CO_2 concentrations. CO_2 storage monitoring is therefore not only a prerequisite for the permitting and regulatory compliance of CCS/CCUS projects, but also the scientific basis for verifying the actual stored volume, supporting carbon trading methodologies, and addressing public concerns [4,5]. Over the life cycle of a project, the pre-injection stage requires the establishment of geological and environmental baselines and the completion of site characterization; the injection stage requires tracking CO_2 plume behavior and ruling out leakage events; the post-injection stage requires verifying long-term storage stability; and the post-closure stage requires retaining the necessary monitoring to support site handover and liability transfer. These stages are progressively linked and together form a complete chain of safety and environmental assurance [4,6]. (In this paper, scenarios involving CO_2 enhanced oil recovery and utilization are referred to as CCUS, whereas pure saline-aquifer storage is referred to as CCS).

1.2. Development of International Monitoring Practice

Since commercial-scale CO_2 injection first began at the Sleipner project in Norway in 1996, global storage monitoring practice has accumulated nearly three decades of experience, which can be summarized in three stages. The early stage focused on technical feasibility and method verification, with research-oriented pilot projects (such as Frio, Ketzin, and Otway) systematically testing various monitoring tools. This was followed by a stage of systematic "measurement, monitoring, and verification" (MMV) constrained by regulations such as the EU CCS Directive and the US EPA Class VI well requirements, in which monitoring programs became increasingly customized and driven by site-specific risk analysis. More recently, a commercial streamlining stage characterized by cost rationalization has emerged, in which projects such as Quest and Snøhvit have narrowed their monitoring portfolios to a small number of high-information technologies targeting the key site-specific risks [4,7,8]. At the same time, over the past decade the integration of monitoring data with numerical simulation has shifted from isolated attempts to routine practice, and the loop of "monitoring data calibrating models, models optimizing monitoring design" has become an international consensus [7,9,10].

1.3. Chinese Practice and Research Gaps

Monitoring practice in China started with national demonstration projects. The Shenhua Ordos CCS demonstration project (cumulative injection of about 302,600 t from 2011 to 2015) established the first "atmosphere–surface–subsurface" three-dimensional monitoring system in China; the CNOOC Enping 15-1 project achieved the first offshore storage monitoring in the country; and the PetroChina Jilin oilfield developed a "three-in-one" safety monitoring technology covering CO_2-EOR scenarios and has maintained safe injection for 16 years. Considering the completeness and comparability of publicly available information, this paper takes the Shenhua CCS demonstration project as the representative domestic sample for in-depth analysis; the Enping 15-1 and Jilin oilfield projects are not included in the item-by-item comparison because of limited public monitoring data, and are left for dedicated follow-up studies. The case is representative in three respects: it is the first full-chain CCS demonstration in a Chinese saline aquifer, it covers a complete baseline–injection–post-injection cycle, and its low-porosity, low-permeability continental sandstone is the reservoir type most widely distributed in China. The conclusions drawn from this case therefore apply to onshore saline-aquifer storage.

From a technical perspective, existing reviews have systematically covered monitoring methods: geophysical monitoring principles [6,11], leakage mechanisms and wellbore integrity [12,13], spatial information technology, offshore storage monitoring and integrated "space–air–ground–well" monitoring [14–16], and shallow groundwater monitoring [17]. From a project perspective, global storage-type case studies and the domestic environmental monitoring and assessment system have been summarized respectively in [1] and [5]. However, most of these studies take a single technology or a single dimension as their entry point, and pay insufficient attention to the overall construction logic of a monitoring technology system—how technologies combine and evolve according to storage type, geological conditions, regulatory context and project stage. Few have placed the systematic experience of typical international projects and the practice of a representative Chinese project within a single framework for item-by-item comparison. For the low-porosity, low-permeability continental saline aquifers that are widely distributed in China, the adaptability of monitoring technologies, the cost structure, and the completeness of the system have not been systematically assessed.

Existing studies have accumulated considerable knowledge at the level of individual technologies, but a systematic comparison centered on "systematic experience of typical international projects versus a representative Chinese project" is still lacking, and the discussion of technology adaptability, cost structure and system completeness under China's continental low-porosity, low-permeability saline-aquifer conditions is particularly thin.

1.4. Scope, Sources, and Methodology

Three principles guided the selection of cases: technological advancement and originality, representativeness of project scale, and completeness of the operating period (covering the whole baseline–injection–post-injection process). The international projects selected comprise offshore deep saline aquifers (Sleipner, Northern Lights, and Tomakomai), onshore deep saline aquifers (In Salah, Decatur/IBDP and Nagaoka), CO_2-EOR and depleted hydrocarbon reservoirs (Weyburn–Midale and Cranfield), and research-oriented pilots (Otway and Ketzin), which are compared with the Shenhua Ordos CCS demonstration project. The data were drawn mainly from public technical reports and peer-reviewed literature (such as the CO2GeoNet and IEAGHG reviews of monitoring methods, the Global CCS Institute monitoring report, and papers from the Greenhouse Gas Control Technologies conference series) [6,7], while the Chinese part is based on published results and project acceptance documents of the Shenhua CCS demonstration project. The analytical framework adopts a four-dimensional perspective of "storage type × geological

conditions × regulatory context × project stage", and the comparison follows uniform dimensions: monitoring system architecture, core technical route, well and monitoring facility strategy, data management and closure, and cost and regulation.

Three attributes differ systematically across the cases. Maturity defines the comparison groups—commercial operation, demonstration and research pilot—within which monitoring intensity is compared, because it tracks maturity more closely than technology; monitoring duration is reported per project (Section 3.1) with frequencies expressed per year of operation; and data availability, which varies with operating age and disclosure practice, is handled by the coding in Section 5. Survey frequencies were taken from the same sources as the deployment coding—operator reporting or peer-reviewed papers by the operating team—and checked against the IEAGHG site catalogue where it records the survey history [18]. Cost figures follow a different rule: each is taken from the single source identified in Section 5.6 and is stated at the boundary defined there, without reconciliation or averaging across sources, and the rows that rest on a secondary compilation rather than on project reporting are identified in the note to that table.

Each of the eleven projects was coded against nine technology items grouped into four monitoring domains—reservoir (repeat 3D seismic; borehole seismic, vertical seismic profiling (VSP) or distributed acoustic sensing (DAS); continuous downhole pressure and temperature), wellbore (integrity logging or testing; wellhead pressure and flow), near-surface (soil gas; shallow groundwater or seawater chemistry; surface or seabed deformation), and atmosphere (atmospheric CO_2 concentration or eddy-covariance flux)—and three cross-cutting attributes (baseline completeness, monitoring-to-model feedback, and data and standards). Each cell takes one of three values: ● when the technology is deployed and documented with parameters in a peer-reviewed paper, an operator report or a technical review (2); ○ when it is mentioned without parameters or deployed intermittently (1); and × when the cited sources contain no record (0). Domain coverage is the sum of item scores divided by twice the number of applicable items (Section 5.7; Table A1). No weighting is applied, because the criteria are non-compensatory: a shortfall in one domain cannot be offset in another. Abbreviations used in this paper are listed in Abbreviation Table.

The four dimensions follow established sources: the site-characterization elements of ISO 27914:2017 [19], the risk-based selection logic of the IEAGHG monitoring assessment [7], and the permitting requirements of US EPA Class VI [20]. They are used as an explanatory device, not a scoring model: projects are grouped, not ranked, and no weighted aggregation across domains is performed. The comparison is reproducible (Table A1 for the coding, Section 5.3 for the frequency benchmarks, and Section 5.6 for the cost boundaries), and it places the Shenhua system item by item: coverage is complete in the near-surface and atmospheric domains, whereas the cross-cutting attributes reach 17% (Section 5.7). The four dimensions are ordered rather than parallel—geological conditions set feasibility; storage type, the macro preference; regulatory context, the strength of obligation and project stage the intensity—which separates transferable methodology from site-specific choice and ties the pathway proposed in Section 6 to China's continental low-permeability saline aquifers.

To address these objectives, this paper answers three progressive questions: first, how the monitoring technical routes of typical international CCS projects differ and why; second, where the monitoring system of the Shenhua CCS demonstration project stands within the international context and what gaps remain; and third, how the monitoring system for China's megaton-scale storage projects should be constructed.

Drawing on the experience of typical international projects and the practice of the Shenhua CCS demonstration project, this paper argues that the technical route of CO_2 storage monitoring is jointly determined by storage type, geological conditions,

regulatory context, and project stage, that no universally applicable scheme can be transplanted from one site to another. Accordingly, the monitoring system for China's megaton-scale storage projects should be built along the pathway of "risk-based hierarchical design + low-cost high-value technology portfolios + monitoring–modeling closure + standards first + data sharing". The remainder of the paper is organized as follows. Section 2 reviews monitoring objectives, technology categories and portfolio logic, and establishes the basic framework for evaluating a monitoring system. Section 3 analyzes the monitoring technology systems of 10 typical international projects and summarizes their common patterns. Section 4 takes the Shenhua Ordos CCS demonstration project as the domestic sample and analyzes the composition and performance of its monitoring system. Section 5 compares the two categories of systems along uniform dimensions, identifies the gaps, and draws implications for China. Section 6 presents the main conclusions and outlook.

2. Overview of the CO_2 Geological Storage Monitoring Technology System

2.1. Monitoring Objectives and Domains

By objective, storage monitoring must answer four scientific questions. The first is quantifying the stored volume—the volume and distribution of CO_2 actually injected and retained underground. The second is ensuring storage safety—whether CO_2 breaches the caprock or induces fault reactivation or wellbore failure. The third is verifying storage conformance—whether the observed plume agrees with model predictions. The fourth is environmental assurance—whether shallow groundwater, soil, surface water, and the atmosphere are affected by leakage [4,7]. These four objectives give rise to different evidential requirements and technical emphases. Quantifying the stored volume requires field-wide imaging and mass accounting of plume distribution and saturation, for which time-lapse seismic, downhole pressure/temperature, and time-lapse gravity are the primary tools. Ensuring storage safety requires continuous surveillance of caprock integrity, fault stability, and wellbore barriers, centered on microseismic monitoring, wellbore integrity logging, InSAR deformation, and above-zone pressure monitoring. Verifying conformance requires systematic comparison between monitoring data and model predictions, with high-resolution observations from VSP/cross-well seismic, tracers, and fluid chemistry providing constraints for model calibration. Environmental assurance requires establishing baselines for shallow groundwater, soil, and the atmosphere, and monitoring them over the long term, mainly through soil gas, groundwater chemistry, eddy covariance and remote sensing [4,7].

In terms of monitoring domain, the objects of monitoring span the "atmosphere and near-surface—shallow subsurface (soil and shallow aquifers)—deep subsurface (overburden, caprock and reservoir)—wellbore system". Different domains require complementary technologies with different spatial coverage and resolution, and no single technology can cover all objectives [9].

2.2. Main Categories of Monitoring Technology and Their Basic Principles

According to technology category and application scenario, CO_2 storage monitoring technologies can be grouped into five categories. Their physical basis, main role, and applicability limits are summarized below and in Table 1. The technology classification and portfolio logic presented in this section provide a uniform basis for the case descriptions in Section 3 and a technical criterion for the system evaluation in Section 5.

(1) Logging and downhole monitoring technologies. Downhole pressure/temperature gauges are based on pressure response and temperature effects: pressure data are the most direct basis for injectivity assessment, stored-volume accounting, and pressure-front

tracking, while temperature is sensitive to Joule–Thomson cooling and phase changes of the injected fluid. Fluid sampling and pH testing exploit the fact that CO_2 dissolved in formation water forms carbonic acid and lowers pH to 4–5; combined with major ions, dissolved inorganic carbon, and $\delta^{13}C$, they help identify water–rock reactions and the origin of CO_2. Geophysical logging, including reservoir saturation tool (RST) and pulsed neutron capture (PNC) logs, identifies near-well saturation from contrasts in high resistivity, low velocity, low density and zero hydrogen index. Distributed optical fiber uses Raman, Brillouin, and Rayleigh backscattering to measure temperature, strain, and acoustic signals, respectively, achieving continuous meter-scale resolution along the entire wellbore. Tracer tests use differences in partition coefficients, diffusion coefficients, and solubility to characterize inter-well migration paths and breakthrough times. This category offers the highest resolution but the smallest coverage; its inherent limitations are the near-well scale and interpretational ambiguity (Table 1) [12,13,21].

(2) Seismic monitoring technologies. Three-dimensional/four-dimensional surface seismic is based on the decrease in acoustic impedance caused by CO_2 displacing brine, and is the dominant technology for plume characterization in saline aquifers. VSP places receivers in the well and observes near the target interval, bypassing the low-velocity zone to improve near-well vertical resolution; cross-well seismic inverts inter-well velocity changes from transmitted observations. Both are well suited to delineating fine plume structure and caprock integrity. Microseismic monitoring locates micro-fracturing events induced by injection to assess fault reactivation and geomechanical risk. The effectiveness of these methods depends on the impedance contrast, reservoir depth, and repeatability of acquisition; in depleted gas reservoirs, the small contrast between CH_4 and CO_2 limits imaging, and the coverage of VSP and cross-well seismic is constrained by the availability of observation wells (Table 1) [6,11,22].

(3) Electromagnetic monitoring technologies. Electrical resistivity tomography (ERT) and controlled-source electromagnetics (CSEM) are based on the increase in resistivity caused by CO_2 displacing highly conductive brine, and invert fluid saturation through Archie's equation, providing an independent petrophysical constraint on seismic interpretation. Time-lapse gravity uses the negative density anomaly produced when CO_2 replaces pore water to estimate plume mass and density distribution. Compared with seismic methods, resolution is lower and the results are sensitive to formation-water salinity, clay content, and electrode coupling, so these methods are mostly supplementary in practice (Table 1) [23,24].

(4) Surface environment and ecological monitoring technologies. Soil gas concentration and flux are measured by concentration gradients and accumulation chambers; eddy covariance obtains the net ecosystem–atmosphere exchange flux from the covariance of turbulent fluctuations and CO_2 concentration; infrared laser gas analysis achieves high-precision rapid measurement based on characteristic absorption spectra; and shallow groundwater chemistry identifies aquifer acidification and element migration through pH, dissolved inorganic carbon, and major ions. Leak discrimination for these indicators relies on long-term baselines and source attribution using $\delta^{13}C$ and noble gas fingerprints, with natural fluctuations and biological processes as the main sources of interference (Table 1) [25–27].

(5) Remote sensing and marine monitoring technologies. Satellite InSAR obtains millimeter-scale surface deformation from radar phase differences, reflecting the mechanical response of the reservoir–caprock system and fault activity. Airborne and satellite spectral imaging and airborne electromagnetics support rapid screening at regional scale. Offshore projects rely on ocean-bottom seismometer and cable arrays (OBS/OBC), seawater chemistry (pH, CO_2 partial pressure, dissolved oxygen), and acoustic bubble-flow detection, forming a "seawater–seabed–reservoir" monitoring chain. InSAR is constrained by

surface coherence, while marine monitoring faces limited baseline data and high implementation costs (Table 1) [14,15,28,29].

Table 1. Principles, monitoring domains and applicability limits of the main CO_2 storage monitoring technologies.

Category	Representative Technology	Main Monitoring Domain	Basic Principle and Main Role	Main Limitations and Failure Conditions
Logging and downhole	Downhole pressure/temperature gauges	Wellbore, reservoir, overburden (AZMI)	Direct pressure and temperature measurement: pressure reflects injectivity and stored volume, temperature is sensitive to Joule–Thomson cooling; continuous and low-cost	Reflects only the near-well region and the pressure-affected zone; sensor drift requires periodic calibration
Logging and downhole	Fluid sampling and chemical/isotopic analysis	Wellbore, reservoir fluids	CO_2 dissolved in formation water forms carbonic acid, lowering pH to 4–5 and changing ion concentrations and dissolved inorganic carbon; $\delta^{13}C$ traces the source	Sampling representativeness and reaction lag; contamination and degassing must be prevented
Logging and downhole	Geophysical logging (including RST/PNC)	Near-well reservoir and caprock	Inverts near-well CO_2 saturation from contrasts in high resistivity, low velocity, low density, and zero hydrogen index	Limited to the near-well region (meter scale); interpretation is difficult in low-porosity, low-permeability reservoirs; CH4 and CO_2 are hard to distinguish
Logging and downhole	Distributed optical fiber (DTS/DAS/DSS)	Entire wellbore	Raman/Brillouin/Rayleigh backscattering measures temperature, strain and acoustic waves, respectively; meter-scale resolution and long service life	Full-length cabling required; DAS signal-to-noise ratio is affected by wellbore noise; installation cost is relatively high
Logging and downhole	Tracer testing	Inter-well, reservoir	Uses differences in partition coefficient, diffusion coefficient and solubility to track migration paths and breakthrough times	Requires injection and sampling windows; adsorption retention and background interference affect quantification
Seismic	3D/4D surface seismic	Reservoir and caprock (field-wide)	The impedance decrease caused by CO_2 displacing brine images the plume; the dominant technology for saline aquifers	Requires sufficient impedance contrast and repeat-acquisition consistency; small CH4–CO_2 contrast in depleted gas reservoirs
Seismic	VSP/cross-well seismic	Near-well, high resolution	Receivers in the well observe near the target interval, bypassing the low-velocity zone to improve vertical resolution	Requires observation wells; coverage limited to the near-well region or a hundred meters between wells
Seismic	Microseismic monitoring	Reservoir, basement	Locates injection-induced micro-fracturing events to assess fault reactivation and geomechanical risk	Depends on the pre-injection background baseline; low event magnitude and relatively large location uncertainty
Electromagnetic	ERT/CSEM	Inter-well, reservoir	CO_2 displacing highly conductive brine raises resistivity, and saturation is inverted through Archie's equation	Lower resolution than seismic; affected by formation-water salinity and clay content
Near-surface environment	Soil gas concentration/flux, eddy covariance	Surface and atmosphere	Determines near-surface CO_2 flux from concentration gradients and turbulent covariance to identify leakage and account for net exchange	Strong interference from natural fluctuations and biological processes; requires long-term baselines and isotopic attribution
Near-surface environment	Shallow groundwater chemistry	Shallow aquifer	Monitors pH, dissolved inorganic carbon, and major ions to identify acidification and element migration caused by dissolved CO_2	Requires pre-injection baselines; affected by rainfall and anthropogenic activity

Remote sensing and geodesy	InSAR/levelling	Surface (kilometer scale)	Radar phase differences provide millimeter-scale deformation, reflecting the mechanical response of reservoir and caprock	Depends on low vegetation and high surface coherence; reflects deformation only and must be interpreted jointly with pressure and seismic data
Marine environment	OBS/OBC, seawater chemistry, bubble-flow detection	Seabed and water column	Acoustic detection of bubble flow and chemical monitoring of seawater pH and pCO_2 to assess marine leakage impacts	Limited baseline data; strong marine disturbance and relatively high cost

2.3. Portfolio Logic and System Construction of Monitoring Technologies

None of these methods measures leakage directly. Surface seismic resolves vertical change only where it is thick enough to alter the reflection response, so a thinning plume margin or a leak confined to a narrow fault can remain below resolution. InSAR resolves line-of-sight displacement at millimeter scale, but only where the surface stays coherent, and a small or deep-seated leak produces no resolvable deformation. Microseismic monitoring records shear slip rather than fluid movement, and events below the detection threshold are missed. A positive anomaly therefore indicates change within the storage complex, not leakage as such; separating the two requires an independent medium—pressure, water chemistry, isotopes, or tracers. For this reason, the portfolios discussed below combine methods of different physical sensitivity rather than repeating one measurement.

The key to designing a monitoring program is not the accumulation of technologies, but the allocation of limited monitoring resources, according to site risk, to the points where uncertainty can be reduced most effectively, while maintaining the complementarity and cross-validation of the multi-domain evidence chain from the subsurface to the near-surface and the atmosphere [7]. A sound portfolio logic can be understood at five levels.

2.3.1. Spatial Multi-Scale Coverage: The "Area–Line–Point" Nesting Logic

Monitoring technologies are structurally complementary in spatial coverage and resolution. Downhole logging, pressure/temperature measurement, and fluid sampling are "point" observations with vertical resolution of centimeters to meters, but their detection range is limited to meters or tens of meters around the well. VSP and cross-well seismic tomography provide a "line/section" scale transition, achieving high-resolution imaging within about a hundred meters of the well. Surface 3D/4D seismic, InSAR, and remote sensing provide "area" coverage at kilometer scale but with limited vertical resolution [6,11]. Mature monitoring systems therefore generally adopt a nested structure of "area for field control, points for calibration, and lines for connection": areal technologies delineate plume boundaries and anomaly zones, point observations in wells provide high-precision calibration and mechanistic constraints, and section technologies bridge the scale gap between them. Reliance on any single category leads to an irreconcilable conflict between wide coverage and high-resolution identification [7].

2.3.2. Mapping from Risk Pathways to Monitoring Tools

Another main line of portfolio design is to configure monitoring tools starting from potential leakage pathways. For caprock pore breakthrough, time-lapse seismic and caprock-interval VSP track the vertical position of the plume, while above-zone monitoring interval (AZMI) pressure monitoring captures precursors of pressure anomalies. For fault and fracture reactivation, microseismic event locations and the InSAR deformation field are combined to assess geomechanical stability. For wellbore failure (abandoned, injection and monitoring wells), wellbore integrity logging, DTS/DAS fiber, and wellhead

tracer monitoring dominate, with integrity testing incorporated into routine periodic operations. For hydrological migration pathways, shallow groundwater chemistry and tracer monitoring are the main tools [3,7,9]. Risk analysis first and monitoring requirements second is the standard paradigm for monitoring program design in advanced international projects (see the cases in Section 3).

2.3.3. Objective-Oriented Portfolio Optimization

The same technology does not have equal value under different monitoring objectives, so portfolio optimization should be objective-driven. For quantifying the stored volume, the main portfolio combines "time-lapse seismic field-wide imaging + continuous downhole pressure/temperature accounting + independent time-lapse gravity constraint", with VSP and cross-well tomography providing saturation calibration. For ensuring safety, "microseismic + wellbore integrity logging + InSAR deformation" forms the core, supplemented by caprock-interval pressure monitoring. For verifying conformance, high-resolution observations from "VSP/cross-well seismic + tracers + fluid chemistry sampling" provide multi-parameter constraints for reservoir model history matching. For environmental assurance, "soil gas concentration/flux + shallow groundwater chemistry + eddy covariance + remote sensing screening" constitutes the near-surface environmental monitoring portfolio [4,7]. Leak discrimination must adhere to the principle of multi-indicator consistency—for example, a soil gas CO_2 anomaly can be judged only after source attribution using $\delta^{13}C$ and noble gas fingerprints, so that natural background fluctuations are not misidentified as leakage [26].

2.3.4. Cost–Information Trade-Off and Technology Readiness Constraints

In terms of maturity, downhole pressure/temperature, conventional logging, soil gas, and groundwater chemistry are established commercial technologies that form the "backbone layer"; 4D seismic, VSP, microseismic, and tracers have been fully validated in industrial-scale projects and form the "enhanced layer"; distributed optical fiber (DAS/DTS), permanent downhole ERT and InSAR are in a phase of rapid uptake and form the "frontier layer"; and low-cost sensor networks and artificial-intelligence anomaly detection are still under development [4,16]. Monitoring cost is usually much lower than capture investment, but high-cost technologies (such as dedicated monitoring wells and high-frequency 3D seismic) do not necessarily deliver proportional gains in monitoring effectiveness. Portfolio design should therefore give priority to mature technologies in order to establish a continuous observation baseline, and then introduce frontier technologies to fill risk-specific gaps, rather than pursuing a complete technology set [7].

2.3.5. Life-Cycle Evolution of the Portfolio

The monitoring portfolio should also evolve dynamically with the project stage. The site characterization and baseline stage follows the principle of "comprehensive and high-precision", investing in high-cost observations such as 3D seismic baselines, environmental backgrounds, and background microseismicity to establish a reference for later anomaly identification. The characterization that precedes these baselines also fixes what the later program must watch: capacity and pressure estimates set the pressure thresholds, the mapped caprock and fault architecture determines whether seismic, microseismic, or InSAR can resolve a leak, and the well inventory fixes the integrity-monitoring burden. Where a national program is still at the feasibility stage, these outputs come first: in the Oltenia region of Romania, storage capacity in a depleted gas field and its pairing with a nearby power plant were established by reservoir simulation [30]. The injection stage shifts to "focusing on key risks", with continuous automated observations such as downhole pressure/temperature and DAS/DTS as the backbone and periodic time-lapse

seismic/InSAR as verification. The post-injection stage converges further to a "sparse, low-frequency, long-term" portfolio dominated by near-surface environmental indicators and a small number of geophysical surveys. The closure and handover stage is governed by the minimum monitoring obligations required by regulation [4,7]. Figure 1 summarizes this overall framework of "monitoring objectives—monitoring domains—representative technologies—life cycle—data and modeling closure", and Table 1 gives the correspondence among main technologies, monitoring domains and roles. The five-level portfolio logic summarized in this section—spatial multi-scale coverage, risk-path mapping, objective orientation, cost–information trade-off, and life-cycle evolution—constitutes the basic yardstick for evaluating monitoring systems in Section 5.

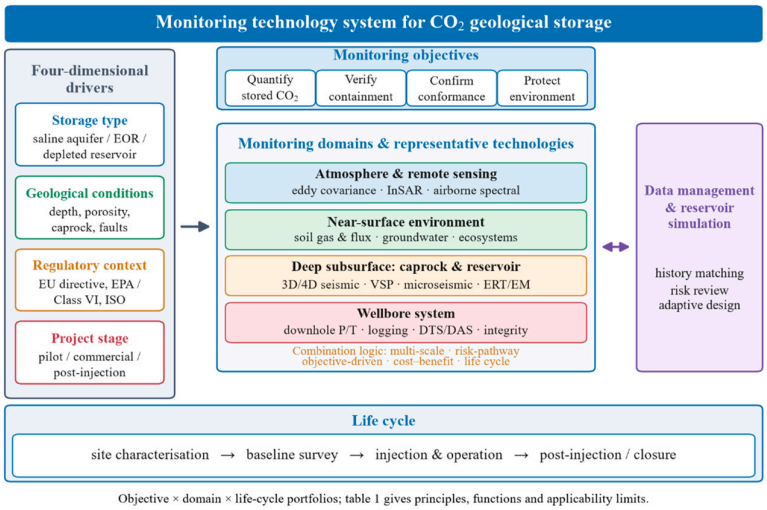


Figure 1. Overall framework of the monitoring technology system for CO_2 geological storage: four-dimensional drivers, monitoring objectives and domains, portfolio logic, life cycle, and the data–model loop (compiled by the authors; technology classification after Refs. [4,6]).

3. Monitoring Technology Systems of Typical International CCS Projects

3.1. Project Selection and Overall Landscape

Following the selection principles in Section 1.4, this study analyzes in depth the 10 typical international projects listed in Table 2. Global monitoring practice has evolved from early research-oriented monitoring focused on "technology verification" to a risk- and regulation-driven "measurement, monitoring, and verification" (MMV) system; monitoring cost is usually much lower than the capital and operating cost of capture, and most projects have completed a rational streamlining from "comprehensive testing" to "precise focus" [7,18]. The following subsections are grouped by storage type and present, for each project, the start-up/injection time, storage type, cumulative stored volume to date, current status, storage depth, composition of the monitoring system, and technical features. At the end of each project, the formation mechanism of its monitoring route is analyzed from the four-dimensional perspective of "storage type—geological conditions—regulatory context—project stage" proposed in Section 1.4; Section 3.6 then summarizes the common patterns along these four dimensions, and Sections 4 and 5 use the same framework to position the Shenhua CCS project and carry out a systematic comparison.

Table 2. Attributes and monitoring systems of the typical international CCS/CCUS projects reviewed.

Project	Country/Storage Type	Reservoir and Depth	Start-Up/Injection Period	Cumulative Stored Volume	Current Status	Regulatory Framework	Monitoring Wells and Facilities	Main Monitoring Frequency	Core Monitoring Technology Portfolio
Sleipner [31,32]	Norway/offshore saline aquifer	Utsira Formation sandstone, about 800–1000 m	Injection since 1996	About 20 Mt	In operation (about 1 Mt/a)	Norwegian Petroleum Act (dedicated CO_2 storage monitoring provisions added in 2014) and pollution control regulations	1 horizontal injection well (15/9-A-16) with wellhead/downhole P/T; no dedicated deep monitoring well; seabed environmental monitoring facilities	About 10 3D seismic surveys, 4 time-lapse gravity surveys, 1 CSEM survey, and 2 seabed imaging surveys during 1994–2016; continuous P/T	4D seismic + time-lapse gravity + CSEM + downhole P/T + seabed environment
Northern Lights [33–36]	Norway/offshore saline aquifer	Johansen Formation sandstone (offshore)	Operational since February 2025	Phase 1 capacity 1.5 Mt/a	Initial operation (25-year plan)	Norwegian EL001 exploration license and pollution control regulations; driven by a containment risk assessment (CRA)	Main injection well 31/5-7 (Eos) plus a backup injection well; an existing appraisal well converted for monitoring/contingency; no new dedicated deep well drilled	4D seismic per regulatory and risk plan (detection threshold about 5 m of plume); continuous P/T; seabed environment and regional surveys	CRA-driven design; 4D seismic + downhole P/T + seabed environment
Tomakomai [37–41]	Japan/offshore saline aquifer	Moebetsu Formation sandstone, about 1100 m	Injection during 2016–2019	About 0.3 Mt	Long-term post-injection monitoring	Japanese METI/JCCS demonstration framework (including induced-seismicity safety assessment)	2 injection wells (IW-1/2) and 3 monitoring wells (OB-1/2/3, with built-in P/T and seismic sensors); 1 OBC cable and 4 OBSs; linked to the Hi-net array	5 seismic surveys from injection to post-injection (Japanese fiscal years 2016–2020); 2 marine environmental baseline campaigns (2013–2014) plus seasonal surveys during operation; continuous P/T	2D/3D/time-lapse seismic + OBC/OBS microseismic + downhole P/T + marine environment
In Salah [42–46]	Algeria/onshore saline aquifer	Carboniferous sandstone, about 1900 m	Injection during 2004–2011	About 3.8 Mt	Injection ceased; post-injection/closure stage	EU CCS Directive 2009/31/EC	3 horizontal injection wells (KB-501/502/503), 5 shallow monitoring wells, and appraisal well KB-5 converted to monitoring	Continuous InSAR (2004–2009); 4D seismic and downhole microseismic; periodic soil gas and groundwater sampling	InSAR + 4D seismic + microseismic + soil/groundwater + wellhead geochemistry
Decatur/IBDP [9,47,48]	USA/onshore saline aquifer	Mt. Simon Formation sandstone, about 2100 m	Injection during 2011–2014	About 1 Mt	Post-injection monitoring	US EPA Class VI (the successor IL-ICCS operates under Class VI and Subpart RR MRV)	CCS1 injection well, VW1 shallow groundwater well and GM1 geophysical monitoring well (31-level array); for IL-ICCS: CCS2 injection and VW2 monitoring wells	18 months of pre-injection background microseismic monitoring; RST/PNC comparison in years 2 and 4; groundwater sampling shifting from quarterly to semi-annual after baseline; continuous DTS	3D seismic + 3D VSP + downhole microseismic + RST + near-surface monitoring

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Nagaoka [49,50]	Japan/onshore saline aquifer	Haizume Formation sandstone, about 1100 m	Injection during 2003–2005	About 10,400 t	Pilot completed; post-injection research	Japanese METI/RITE pilot framework	1 injection well (CO_2-1) and 3 observation wells (CO_2-2/3/4)	Monthly logging in observation wells (induction/gamma/neutron/sonic); 2 cross-well tomography surveys (at 3200 t and 6200 t); about 10 years of post-injection monitoring	Cross-well seismic tomography + logging + fluid sampling + soil gas
Weyburn–Midale [51–53]	Canada/CO_2-EOR	Midale carbonate, about 1450–1500 m	Injection since 2000	More than 30 Mt	In continuous operation	Saskatchewan oil, gas and greenhouse gas regulatory framework	177 injection wells and a dense production well network (wellbore integrity as the focus)	4D/3C seismic (1999 baseline and 2001/2002/2004/2007); 14 geochemical sampling campaigns (2000 baseline, 11th in 2004, 14th in 2009); tracer tests	4D/3C seismic + VSP + wellbore integrity + tracers + geochemistry
Cranfield [54–56]	USA/CO_2-EOR	Tuscaloosa Formation sandstone, about 3100 m	Injection during 2008–2014	About 3 Mt	Post-closure monitoring	US EPA Class VI and the SECARB collaboration framework	Injection wells and a production well network (using existing wells)	RST injection profiles; time-lapse 3D and cross-well seismic; 3 years of post-injection monitoring	Time-lapse seismic + RST + borehole gravity + tracers + near-surface source attribution
Otway [57–59]	Australia/research pilot	Waarre Formation depleted gas reservoir and others, about 1500–2000 m	Multi-stage since 2008	About 0.1 Mt	Frontier technology development	Australian Commonwealth and Victorian state regulatory framework (research pilot)	Injection wells (CRC-1 and others) and monitoring wells (Naylor-1 and others) with U-tube sampling	Stage 1: multiple time-lapse 3D/VSP surveys; Stage 2: residual-gas cycling tests; Stage 3: permanent seismic orbital vibrators (SOV) and continuous multi-well 4D DAS VSP	Multiple tracers + DAS/DTS + 4D seismic/VSP + continuous atmosphere and soil monitoring
Ketzin [60–62]	Germany/research pilot	Stuttgart Formation sandstone, about 630–650 m	Injection during 2008–2013	About 67,000 t	Closed, long-term monitoring	EU CO2SINK project and EU storage directive framework	1 injection well (Ktzi 201) and 2 monitoring wells (Ktzi 200/202 with permanent ERT electrode arrays)	Continuous VERA cross-well ERT; multiple 4D/2D seismic surveys (2007 baseline); periodic groundwater sampling at 35 and 55 m	Permanent ERT (VERA) + 4D seismic + groundwater + well integrity

3.2. Offshore Deep Saline-Aquifer Projects

(1) Sleipner (Norway). Sleipner started operation in September 1996 and is the world's first and largest commercial saline-aquifer storage project. CO_2 is captured from natural gas sweetening at Sleipner Vest and injected through a near-horizontal well into the high-porosity, unconsolidated Utsira Formation sandstone aquifer about 1012 m below the seabed. Cumulative storage to date is about 20 Mt at an annual injection rate of about 1 Mt, and the project remains in continuous operation [31]. Its monitoring system is centered on time-lapse (4D) seismic: after the 1994 baseline survey, about 10 repeat 3D seismic surveys were acquired up to 2016, together with four time-lapse seabed gravity surveys (constraining plume density and temperature), one CSEM survey, and two seabed imaging surveys, supplemented by downhole pressure/temperature and seabed chemical monitoring. These can resolve CO_2 accumulations of about 1 m vertically and 10 m laterally, and have clearly imaged the layered plume evolution controlled by multiple mudstone baffles (Figure 2) [31,32]. The project released the Sleipner 2019 benchmark model to the global modeling community. Its technical feature is that the exceptional imaging performance of time-lapse seismic benefits from favorable seismic conditions—shallow burial, high porosity and permeability, and a strong CO_2–brine impedance contrast—so extrapolation of the method requires careful evaluation against site conditions [7]. From the four-dimensional perspective, Sleipner's technical route was shaped jointly by commercial offshore saline-aquifer storage, favorable shallow high-porosity high-permeability seismic conditions, the dedicated monitoring requirements of the Norwegian Petroleum Act, and nearly three decades of long-term operation. These conditions produced a high-information monitoring portfolio centered on time-lapse seismic and combined with multiple geophysical methods.

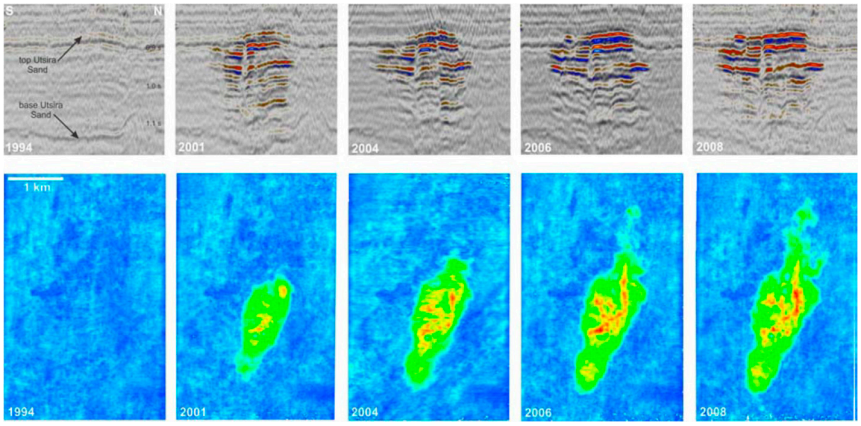


Figure 2. Time-lapse seismic images of CO_2 plume evolution at the Sleipner storage site, 1994–2008 (after Ref. [63]).

(2) Northern Lights (Norway). Northern Lights is the world's first open cross-border CO_2 transport and storage infrastructure, operated by a joint venture of Equinor, Shell, and TotalEnergies as the transport and storage component of Norway's full-scale Longship CCS program (Figure 3). The project began storage-potential evaluation in 2018, mechanically completed its onshore receiving facilities in September 2024, and received its first CO_2 carrier in February 2025, becoming fully operational. The storage interval is the offshore Johansen Formation sandstone (sealed by the Drake Formation shale); Phase 1 has an injection capacity of 1.5 Mt/a with a planned operating life of 25 years and the potential to expand to 5 Mt/a [33]. Its monitoring program is driven by a containment risk assessment (CRA), forming a closed loop of "risk identification, monitoring requirements,

technology selection, and response planning"; 13 potential leakage pathways were identified, each with a corresponding barrier and monitoring response strategy. Subsurface monitoring is centered on time-lapse seismic (a plume about 5 m thick is considered detectable), supplemented by downhole pressure/temperature and seabed environmental monitoring. An existing appraisal well was converted to provide monitoring functions rather than drilling a new dedicated deep monitoring well, reflecting the design philosophy of "multiple functions from few wells" and risk orientation [34–36]. Its distinctive feature is that a monitoring program serving multiple open-access clients must simultaneously satisfy differentiated compliance requirements and commercial flexibility, making it representative of a new generation of commercial storage monitoring [34]. From the four-dimensional perspective, Northern Lights' technical route was determined jointly by an open offshore saline-aquifer infrastructure, a faulted and structurally complex reservoir (cross-fault containment), the stringent compliance requirements of Norwegian exploration-license and pollution-control regulations, and its early operational stage, resulting in a CRA-driven hierarchical monitoring design that accommodates the differentiated needs of multiple clients.

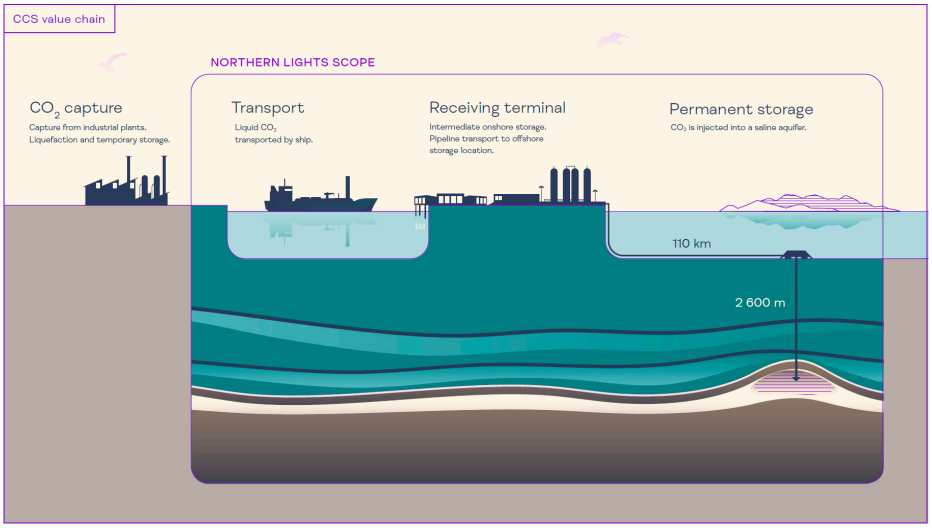


Figure 3. Overview of the Northern Lights CO_2 transport and storage value chain (ship unloading—onshore buffer—subsea pipeline—subsea injection and monitoring) (after Ref. [33]).

(3) Tomakomai (Japan). Tomakomai is the first fully operating offshore storage demonstration project in Asia. Design and construction began in 2012, injection started in April 2016 and ended in December 2019; a total of 300,012 t of CO_2 was injected into the shallow Moebetsu sandstone (about 1100 m deep), while the deeper Takinoue volcanic formation was abandoned after a trial injection of only 98 t because of excessively low permeability. The project is now in long-term post-injection monitoring [37,38]. It established a multi-level "air–seawater–seabed–reservoir–deep structure" integrated land–sea monitoring system: two injection wells and three monitoring wells (all equipped with pressure/temperature and seismic sensors), one permanent ocean-bottom cable (OBC), and four ocean-bottom seismometers (OBS) connected to the Japanese Hi-net array, and multiple 2D/3D and time-lapse seismic surveys before and after injection, with marine environmental monitoring covering seasonal seawater chemistry, biological, and geological indicators at twelve offshore and three onshore stations (Figure 4) [37,39,40]. The monitoring results showed that time-lapse seismic amplitude anomalies clearly reflected plume expansion confined to the reservoir; all microseismic events were deeper than 5 km, so injection did not induce significant seismicity; and the 2018 Hokkaido Iburi

earthquake (about M6.6) caused no facility damage or leakage [41]. Its distinctive feature is that the integrated land–sea system provides a model for storage monitoring in seismically active offshore areas, while the experience of "the deep reservoir being un-injectable and the shift to a shallow one succeeding" highlights the decisive role of injectivity assessment in site selection [39]. From the four-dimensional perspective, Tomakomai's technical route was shaped jointly by offshore saline-aquifer demonstration, the special geological conditions of a dual reservoir (shallow sandstone and deep volcanic rock), the pressure to demonstrate induced-seismicity safety arising from its location in the circum-Pacific seismic belt, and its transition from completed injection to the post-injection stage, producing an integrated land–sea system featuring microseismic and marine environmental monitoring.

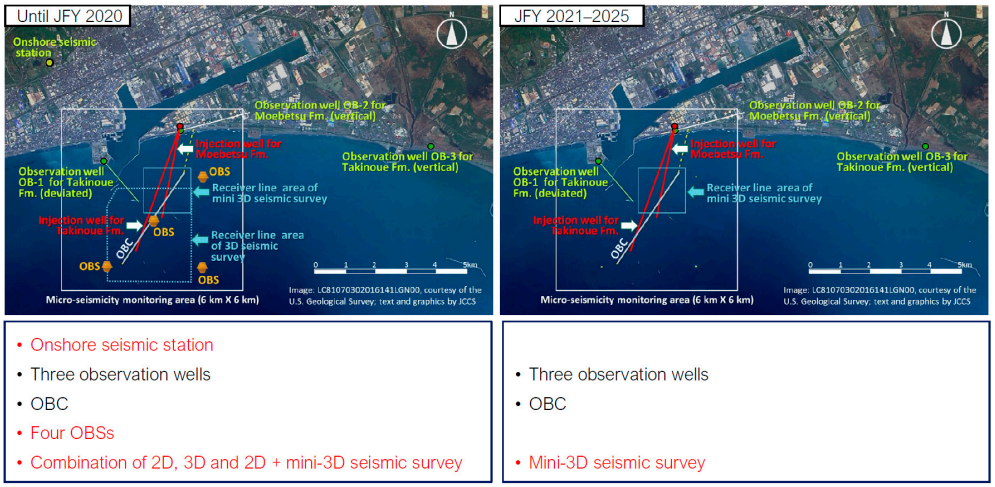


Figure 4. Monitoring system and facility layout of the Tomakomai CCS demonstration project (after Ref. [40]).

3.3. Onshore Deep Saline-Aquifer Projects

(1) In Salah (Algeria). In Salah is located in the Krechba gas field in the Sahara Desert. Between 2004 and 2011, about 3.8 Mt of CO_2 was injected through three horizontal wells into a Carboniferous sandstone aquifer about 1900 m deep (reservoir thickness about 20 m). After injection stopped in 2011, the project entered long-term post-injection/closure monitoring, and it is one of the few industrial projects to have completed the full baseline–injection–closure process [42,43]. Its monitoring system is characterized by satellite InSAR surface deformation as the flagship technology: during injection, surface uplift of up to about 20 mm was detected around the injection wells, whereas the gas-producing area subsided by about 5 mm (Figure 5). An anomalous double-lobe pattern above well KB-502, separated by a trough aligned with the maximum horizontal stress direction, forced the conceptual model to be revised from uniform porous-medium flow to fault/fracture-controlled flow [42]. This was complemented by 4D seismic, downhole microseismic, wellhead pressure/flow and ^{13}C tracer, five shallow monitoring wells, and soil gas/groundwater monitoring [44,45]. Its technical feature is that the success of InSAR depends heavily on the strong interferometric coherence of a low-vegetation desert surface, and that monitoring data can reveal previously unknown geological features; the project also provided valuable whole-life-cycle cost–benefit data—for example, the tiltmeter network was abandoned because its cost-effectiveness was insufficient [43,46]. From the four-dimensional perspective, In Salah's technical route was shaped jointly by onshore industrial saline-aquifer storage, a low-permeability fractured reservoir with a strongly coherent desert surface, the EU CCS Directive framework, and a completed life cycle, making

InSAR its flagship technology and the project a benchmark case for monitoring cost-effectiveness assessment.

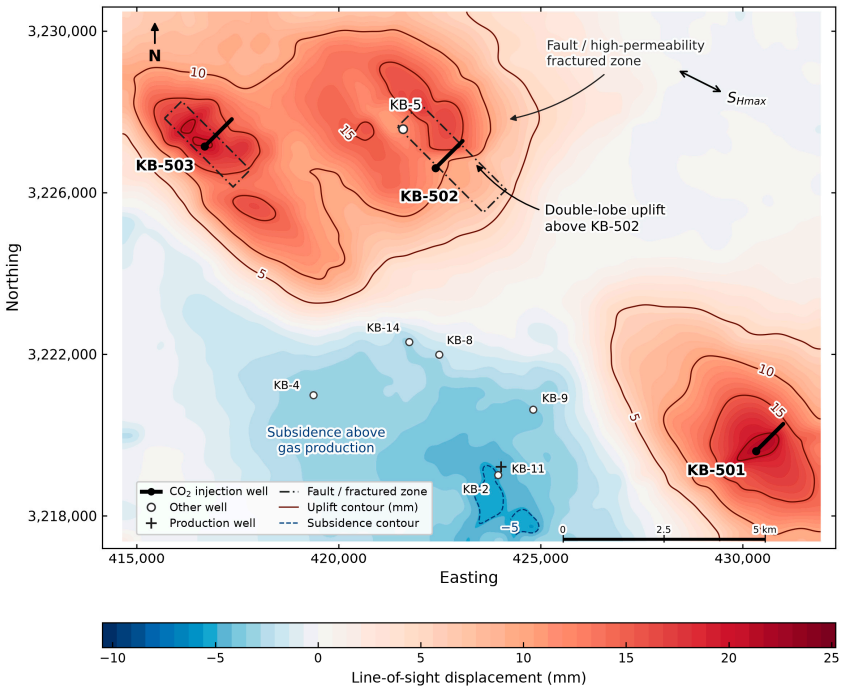


Figure 5. InSAR line-of-sight displacement around the three injection wells at the In Salah site, redrawn from the figure in Ref. [42]. Solid contours, uplift of 5–20 mm; dashed contour, subsidence of −5 mm; dash-dot outlines, fault/high-permeability fractured zones after Refs. [42,64].

(2) Decatur/IBDP (USA). The Illinois Basin Decatur Project (IBDP) started in 2007, with injection beginning in November 2011 and ending in 2014; about 1 Mt of CO_2 was injected into the Mt. Simon Formation sandstone aquifer about 2100 m deep, and the project is now in continuous post-injection monitoring. Its monitoring, verification, and accounting (MVA) system follows the principle of "systematically increasing spatial coverage and resolution as the project progresses": a 2D seismic pre-drill assessment, 3D three-component surface seismic, and a 3D VSP baseline (2010), and 18 months of pre-injection background microseismic monitoring were completed in sequence; during injection, time-lapse VSP and microseismic monitoring were carried out using a 31-level downhole three-component geophone array in monitoring well GM1, complemented by RST/PNC logging, soil flux, atmospheric and shallow groundwater monitoring to form multi-domain coverage. The site adjoins an active ADM corn-processing plant, where industrial vibration and traffic noise interfere with precise geophysical measurement; the project overcame these through optimized sensor deployment and data-processing innovations (wavelet unification and wavefield subdivision), providing a direct reference for monitoring in industrial-site environments [9,47]. Of note is a warning: in March 2024, the monitoring verification well VW2 of the successor commercial project IL-ICCS (Illinois Industrial Carbon Capture and Storage) suffered corrosion leakage at a depth of about 1524 m (leakage revised to 2670–3940 t, with fluids entering the Ironton–Galesville Formation above the caprock); ADM subsequently suspended injection and received a notice of violation from the EPA. Although the wells were built to Class VI standards with regular integrity monitoring, the long-term corrosion risk of monitoring wells was not fully avoided, revealing the dual role of a monitoring well as both an observation window and a possible man-made leakage pathway (Figure 6) [48]. From the four-dimensional perspective, IBDP's technical

route was determined jointly by onshore research-demonstration storage, a thick high-porosity high-permeability sandstone accompanied by an active industrial-site setting, the stringent US EPA Class VI and Subpart RR regulatory system, and the completion of the demonstration phase with its successor entering commercial operation, producing an MVA strategy featuring staged geophysical characterization and long-period baseline monitoring; the ADM leakage event directly exposed the weakness of well facilities in long-term integrity.

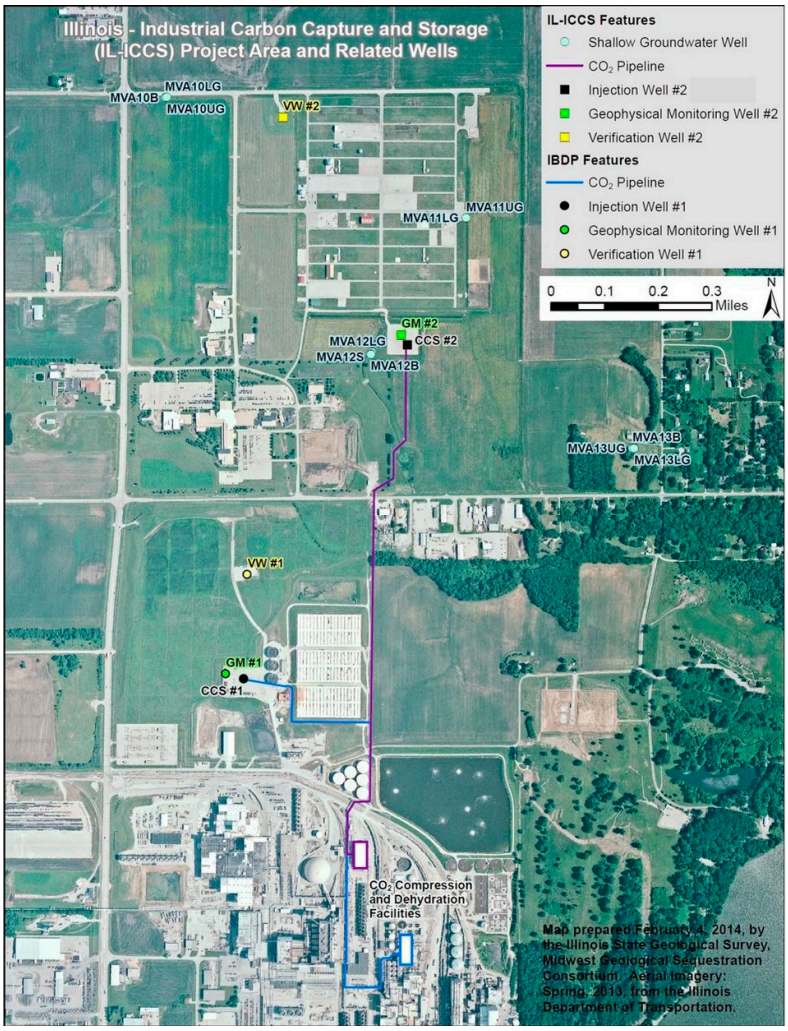


Figure 6. Well locations and monitoring-well layout of the Decatur/IBDP site (after Ref. [48]).

(3) Nagaoka (Japan). Nagaoka is Japan's first onshore storage pilot. It started in 2000, and about 10,400 t of CO_2 was injected between July 2003 and early 2005 into the Haizume Formation sandstone aquifer about 1100 m deep; from 2005 to 2015, post-injection monitoring and research continued for a full decade. Its monitoring system is centered on time-lapse cross-well seismic tomography: one injection well and three observation wells were configured, and tomography was performed between two observation wells 160 m apart, clearly inverting the evolution of the CO_2 saturation profile in two surveys after the injection of 3200 t and 6200 t (Figure 7). This was complemented by monthly geophysical logging (induction, gamma, neutron, and sonic), fluid sampling, soil gas (measured 0.34–2.95 mol%, below the background of 3–4 mol%), and shallow water monitoring. Besides demonstrating the high-resolution imaging capability of cross-well seismic, the project obtained indicative evidence of dissolution and mineral trapping, and its long-period

post-injection dataset has become a valuable sample for assessing how secondary trapping mechanisms strengthen over time [49,50]. From the four-dimensional perspective, Nagaoka's technical route was supported jointly by its onshore pilot positioning, shallow high-porosity high-permeability sandstone conditions, a government-funded research mandate, and a 10-year post-injection stage, forming a small-scale high-precision monitoring paradigm centered on cross-well seismic tomography.

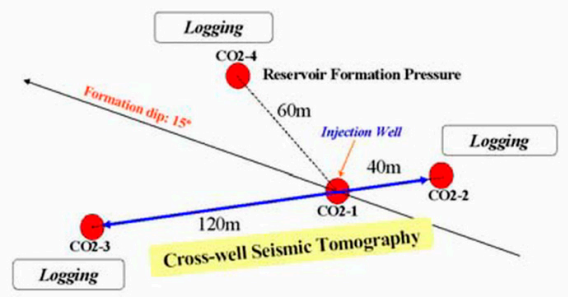


Figure 7. Layout of the injection and observation wells and the cross-well seismic tomography at the Nagaoka site (after Ref. [65]).

3.4. CO_2-EOR and Depleted Hydrocarbon Reservoir Projects

(1) Weyburn–Midale (Canada). Weyburn–Midale started operation in 2000 and is the world's largest CO_2-EOR storage project. CO_2 is injected into the Midale carbonate reservoir (about 1450–1500 m); cumulative storage to date exceeds 30 Mt (with a plan exceeding 40 Mt) and the project is in continuous operation. Unlike saline-aquifer projects, the EOR setting has a dense well network (177 injection wells), and wellbore integrity was assessed as the most likely leakage pathway. On this basis, the project established a risk-oriented strategy in which 4D seismic defines the plume extent, a 500 m radius around wells delineates the risk assessment zone, monitoring is scored (1–5) according to cumulative injection, overlapping zones are weighted, and monitoring is deployed hierarchically (Figure 8). For geochemical monitoring, a 3D three-component time-lapse seismic baseline was completed in 1999 and a geochemical baseline was sampled in August 2000, with the 11th and 14th monitoring samplings completed in 2004 and 2009, respectively, complemented by aqueous (naphthalene sulfonate) and gas-phase tracers to characterize inter-well flow patterns and migration times [51,52]. In the widely noted Cox's Farm leakage allegation, the project compared soil gas composition, concentration and $\delta^{13}C$ between monitoring and control areas (on a 96 m grid) together with noble gas fingerprints, confirming that the anomalous CO_2 was of natural origin rather than injected leakage; this became a landmark case of responding to public concerns with multi-dimensional geochemical evidence [51]. Its distinctive feature is that the dense well network in an EOR setting provides both monitoring convenience and wellbore leakage risk, so risk-graded management became the project's main means of controlling cost and risk [52,53]. From the four-dimensional perspective, Weyburn–Midale's technical route was determined jointly by commercial CO_2-EOR operation, a strongly heterogeneous carbonate reservoir with a dense well network, the Saskatchewan regulatory framework, and more than 20 years of long-term operation, shifting the monitoring focus to graded wellbore integrity assessment and geochemical tracing rather than large-area geophysical imaging.

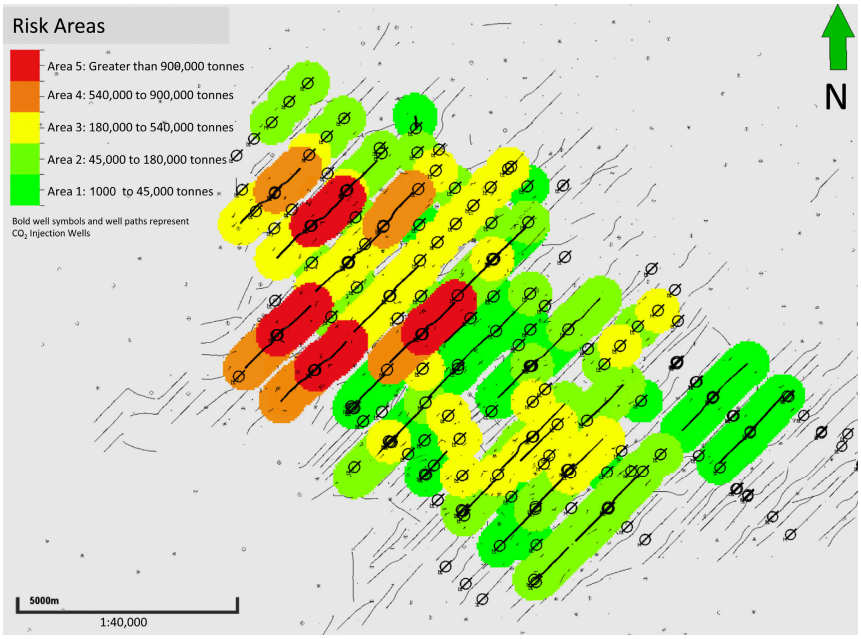


Figure 8. Risk-based monitoring zonation of the Weyburn–Midale field (after Ref. [53]).

(2) Cranfield (USA). Cranfield is a CO_2-EOR and storage demonstration project under the Southeast Regional Carbon Sequestration Partnership (SECARB) framework. Injection (Phase II) began in 2008 and ended in 2014, with about 3 Mt of CO_2 injected into the Cretaceous Tuscaloosa Formation sandstone about 3100 m deep; after closure in 2015, the field was taken over by the operator, and post-injection monitoring continued for three years. Its monitoring system includes time-lapse 3D seismic, RST logging of injection profiles, time-lapse cross-well seismic and borehole gravity, together with systematic near-surface environmental monitoring. RST logging revealed that CO_2 preferentially entered specific high-permeability flow units in the D–E interval, directly confirming the first-order control of reservoir heterogeneity on plume distribution (Figure 9). The project also established a gas source attribution framework combining gas composition ratios, $\delta^{13}C$ and $\Delta^{14}C$, successfully distinguishing deep injected gas from shallow biogenic gas [54,55]. Post-injection analysis showed that residual and dissolution trapping strengthened progressively after injection ceased, providing multiple safeguards for long-term storage safety [56]. From the four-dimensional perspective, Cranfield's technical route was shaped jointly by CO_2-EOR and storage demonstration, fluvial–deltaic strongly heterogeneous sandstone conditions, the US Department of Energy research collaboration framework, and its transition from closure to the post-injection stage, forming a monitoring scheme featuring high-resolution reservoir characterization and gas source attribution.

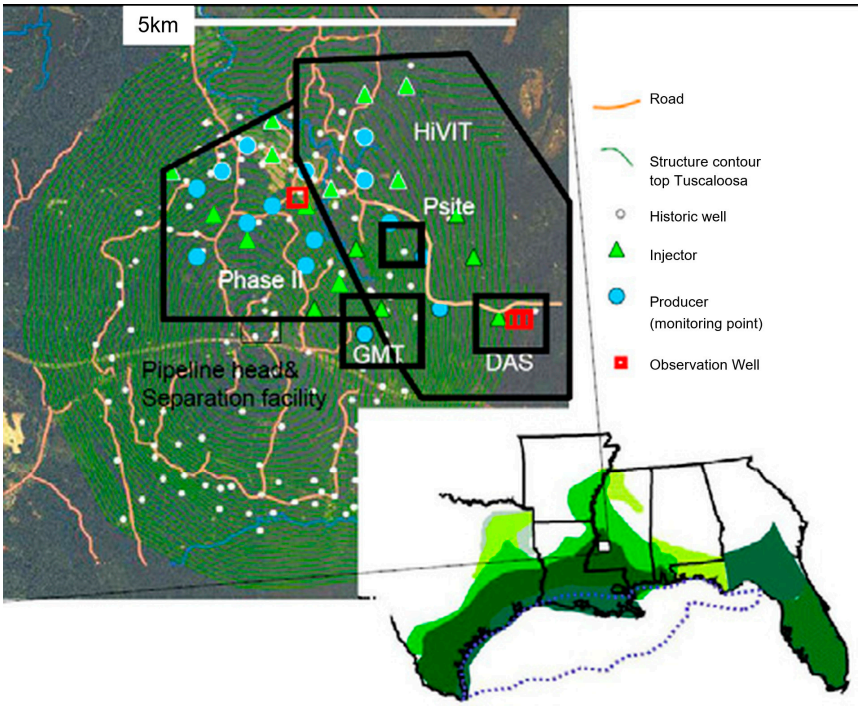


Figure 9. Location of the SECARB experimental study areas at the Cranfield site (after Ref. [66]).

3.5. Research-Oriented Pilot Projects

(1) Otway (Australia). The CO2CRC Otway project is the world's most influential "field laboratory" for storage monitoring. Stage 1 (2008–2009) injected 65,445 t of CO_2 into the Waarre Formation depleted gas reservoir (about 1500–2000 m); Stage 2 (2011–2016) investigated residual gas saturation and dissolution trapping; and Stage 3 (from 2016) focuses on the development of low-cost monitoring technologies, with the project still progressing [57]. Its monitoring system features a combined multi-tracer strategy (CD_4, Kr, SF_6, and tetrafluoroethane) and geochemical forward verification, complemented by 4D seismic/VSP, distributed optical fiber (DAS/DTS), and continuous atmospheric and soil monitoring; Stage 3 further developed an automated low-cost monitoring scheme based on permanent shallow seismic orbital vibrators (SOV) and multi-well 4D DAS VSP (Figure 10) [58]. The measured CO_2 breakthrough time fell at the earlier end of the predicted range, confirming the control of high-permeability channels on migration velocity [59]. Its distinctive feature is that it does not target injection scale but focuses on field verification and cost optimization of frontier monitoring technologies; several technologies later applied in commercial projects were first field-tested at Otway [57,58]. From the four-dimensional perspective, Otway's technical route was determined jointly by its research-pilot positioning, multi-type reservoir conditions (depleted gas reservoir and saline aquifer), a self-sustaining regulatory environment led by research institutions and multi-stage continuous progress, making it both a verification platform for frontier monitoring technologies and an incubator for low-cost monitoring schemes.

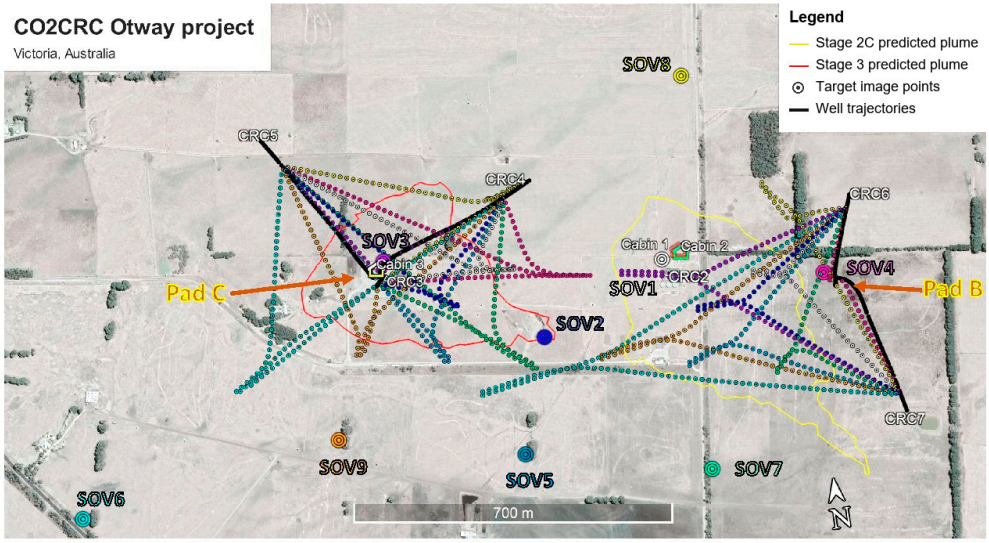


Figure 10. Layout of the wells and surface orbital vibrators (SOVs) at the Otway Stage 3 site; the dotted lines join the target image points, colour-coded by SOV, and the yellow and red outlines are the predicted Stage 2C and Stage 3 plume contours simulated for 15,000 t of CO_2 (after Ref. [67]).

(2) Ketzin (Germany). Ketzin is the first onshore storage pilot project in continental Europe (the core site of the EU CO2SINK project). It started in 2004, completed its 3D baseline seismic survey in 2007, and injected about 67,000 t of CO_2 into the Triassic Stuttgart Formation sandstone about 630–650 m deep between June 2008 and August 2013, after which it entered the closure and long-term monitoring stage [60]. Its monitoring system is characterized by a permanent vertical electrical resistivity array (VERA) deployed in the two monitoring wells Ktzi 200/202, enabling continuous inter-well resistivity monitoring throughout injection (Figure 11); this is complemented by multiple 4D/2D seismic surveys (showing preferential westward migration of CO_2, reflecting reservoir heterogeneity), groundwater sampling at 35 and 55 m depth and well-integrity monitoring spanning the whole life cycle [61]. Static geological models and dynamic simulations were regularly updated as monitoring data accumulated, and the history-matched simulations were reported to be in good agreement with the monitoring results, making Ketzin a reference case for monitoring–modeling closure [62]. From the four-dimensional perspective, Ketzin's technical route was determined jointly by its research-pilot positioning, shallow heterogeneous channel sandstone conditions, the EU CO2SINK project, storage directive framework, and its closure and entry into long-term monitoring, establishing the maturity of permanent downhole ERT and forming a multi-method combined monitoring paradigm covering the whole life cycle.

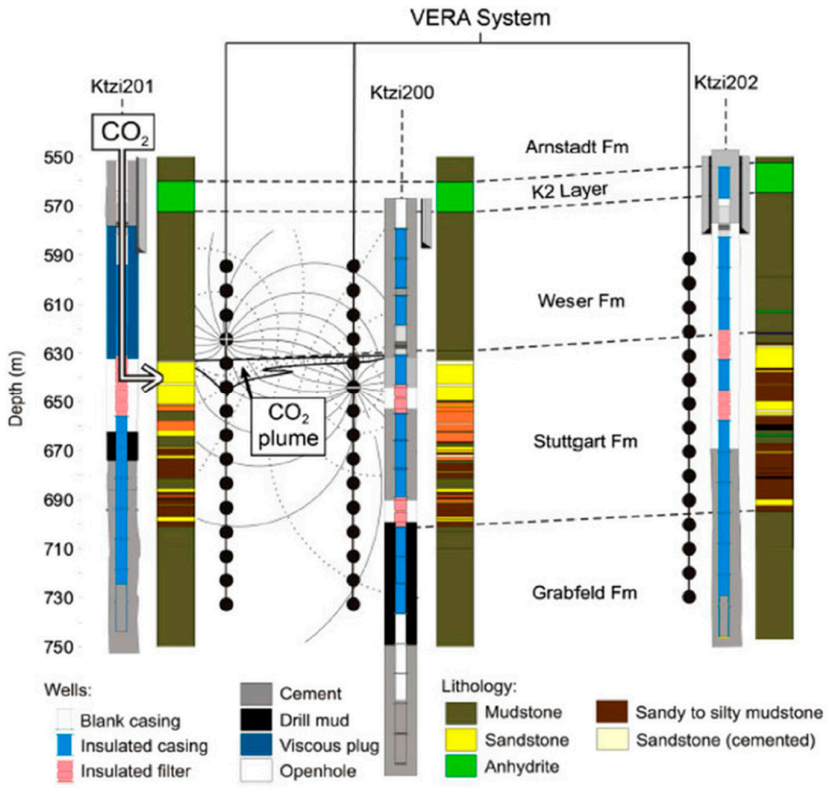


Figure 11. Installation and layout of the vertical electrical resistivity array (VERA) at the Ketzin site (after Ref. [24]).

3.6. Summary: Common Patterns of the International Cases

Following the four-dimensional framework of Section 1.4, the international cases exhibit four common patterns. This section states the patterns themselves only; the interaction of the four factors and the explanation of their causes are left to Section 5.

(1) Storage type determines the macro preference of the technical route. Deep saline aquifers are centered on geophysical imaging—offshore projects rely mainly on time-lapse seismic supplemented by gravity, electromagnetic and seabed environmental monitoring, whereas onshore projects have developed combinations of InSAR, permanent ERT, VSP, and microseismic. In CO_2-EOR and depleted hydrocarbon reservoirs, the monitoring focus shifts to wellbore integrity and geochemical tracing; research-oriented pilots are oriented towards method verification [7,8,10,31–46,48,49,51–54,56–62].

(2) Geological conditions determine the effectiveness of individual technologies. The time-lapse seismic at Sleipner, the InSAR at In Salah, and the cross-well tomography at Nagaoka all presuppose specific site conditions [7].

(3) Regulatory context determines the form of monitoring and the strength of obligations. The Norwegian Petroleum Act gave rise to a CRA-driven monitoring loop, the US EPA Class VI and Subpart RR impose life-cycle measurement, reporting, and verification (MRV) obligations, and the EU storage directive promotes whole-life-cycle coverage [9,19].

(4) Project stage determines monitoring intensity and portfolio. Pilot and demonstration projects emphasize comprehensive verification, commercial projects converge on a small number of high-information technologies, and the post-injection stage shifts to sparse, low-frequency monitoring [7].

All cases show that monitoring serves both “verification” and “discovery” functions (the double-lobe deformation at In Salah revealed fault-controlled flow; high-permeability channels at Cranfield affected plume distribution), and that monitoring wells themselves

must be included in integrity risk management (the ADM IL-ICCS event) [48]. Figure 12 gives the distribution: 3D/4D seismic is the most widely used (9/10), followed by fluid chemistry and isotopic tracing, and by soil gas/flux monitoring (6/10 each), while downhole pressure/temperature monitoring appears in 4/10.

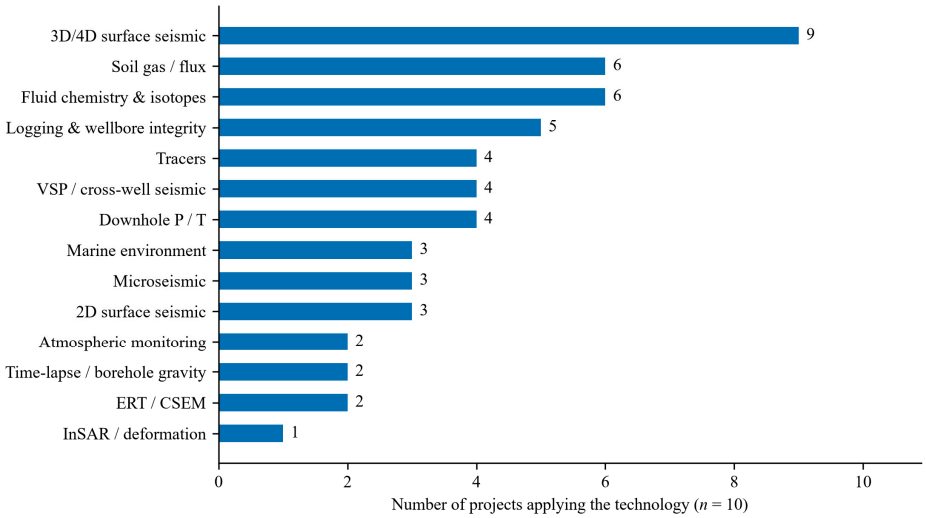


Figure 12. Deployment frequency of monitoring technologies across the ten typical international projects reviewed in this paper (compiled from Table 2 and Section 3; $n = 10$).

4. Monitoring Technology System of the Shenhua Ordos CCS Demonstration Project

4.1. Project Overview and Geological Conditions

The Shenhua Ordos CCS demonstration project (now under China Energy Investment Corporation) is located in Ejin Horo Banner, Ordos City, Inner Mongolia. Built in association with a direct coal liquefaction plant, it is the first full-chain deep saline-aquifer storage demonstration project in China and the first full-chain CCS project in Asia [68–70]. The storage site lies in the Ordos Basin, where the structure is gentle and faults are poorly developed. The target intervals are the Mesozoic Liujiagou Formation sandstone and the Paleozoic Majiagou Formation carbonate below 1600 m, sealed by the Zhifang Formation mudstone; the reservoir is typically low-porosity and low-permeability and belongs to the continental saline-aquifer type widely developed in China [70]. CO_2 comes from the flue gas of direct coal liquefaction, is purified to 99.99%, and transported by cryogenic tanker (about −20 °C, 2 MPa) to the injection site about 13 km from the plant. The site has one injection well (Zhong Shen Zhu 1) and two nearby monitoring wells (Zhong Shen Jian 1 at 70 m and Zhong Shen Jian 2 at 31.61 m from the injection well). Supercritical CO_2 injection began in January 2011, and about 302,600 t was injected between 2011 and 2015, achieving the world's first multi-layer injection and stratified monitoring in a deep low-porosity, low-permeability saline aquifer [68,71].

Earlier studies laid the foundation for monitoring program design: a three-dimensional geological model built from seismic interpretation horizons and drilling stratigraphic constraints characterized the structural framework and reservoir–seal assemblage of the injection area, providing the site characterization basis for multi-layer injection and stratified monitoring [72]; comparison between a leakage-diffusion prediction model and field measurements from a CO_2 leakage monitor determined the leakage identification threshold and emergency monitoring locations [73]; and multi-well co-injection numerical

simulation demonstrated the feasibility of storage at a scale above 0.5 Mt in this type of low-permeability sandstone reservoir [74].

Injection pressure was initially about 13 MPa because of the poor reservoir permeability, but it declined continuously as injection proceeded—to about 10 MPa in 2012 and about 5.2 MPa in 2014. Sampling analysis and subsequent studies showed that CO_2 injection induced water–rock reactions and improved the pore structure, forming a dynamic injectivity pattern of "permeability increasing during injection, strength increasing after cessation"; experimental studies of CO_2–brine–rock interactions further revealed, at the pore scale, the control of mineral dissolution and precipitation on permeability evolution [75,76].

4.2. The "Atmosphere–Surface–Subsurface" Three-Dimensional Monitoring System

Supported by a National Key Technology R&D Program project, the project brought together industry–university–research partners—the National Institute of Clean-and-Low-Carbon Energy (management and coordination), Peking University (downhole monitoring), BGP Inc., Zhuozhou, China (3D/VSP seismic monitoring) and the Institute of Environment and Sustainable Development in Agriculture, CAAS (surface ecological impact research)—and built a three-dimensional monitoring technology system covering the three spatial levels of "atmosphere–surface–subsurface". Monitoring spans the baseline, injection, and post-injection stages, and an information platform integrating CO_2 storage monitoring, safety assessment, and leakage early-warning and response was established to enable online integration and automatic warning of multi-source monitoring data [68]. In designing the monitoring system, the project conducted an environmental baseline survey in accordance with the China Society for Environmental Sciences specification "Risk assessment specification for leakage of carbon dioxide geological utilization and storage", and deployed routine monitoring only after the baseline was established, reflecting the standardized principle of "baseline first" [5]. The following subsections describe the monitoring deployment and main results at the three levels of subsurface (reservoir and caprock), wellbore, and near-surface and atmosphere (Section 4.3).

4.3. Hierarchical Monitoring Deployment and Main Results

(1) Subsurface monitoring (reservoir and caprock): time-lapse VSP as the core. Three VSP seismic surveys were conducted in 2011 (pre-injection baseline), 2013 (cumulative injection of about 130,000 t), and 2014 (cumulative injection of about 250,000 t). The time-lapse results showed that the P-wave event beside the injection well shifted downward by about 2–3 ms and that the lateral migration range of CO_2 within the injection interval expanded from about 350 m in 2013 to about 450 m in 2014 (Figure 13b), while comparison of the three surveys across the caprock interval at about 950 m depth, well above the injection interval, revealed no seismic wavefield anomaly, demonstrating that CO_2 did not breach the main caprock (Figure 13a). The time-lapse VSP acquisition and processing workflow (including cross-correlation travel-time picking and wavelet consistency processing) has been developed into a systematic technical method [77,78].

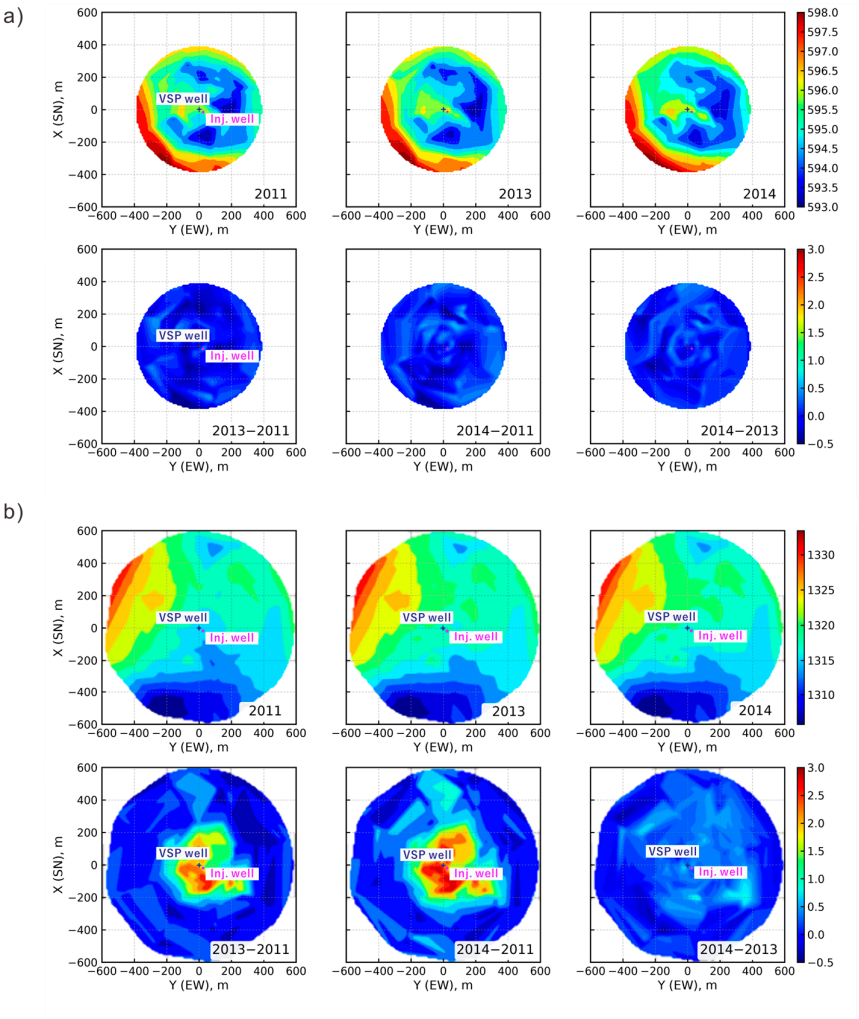


Figure 13. Time-lapse VSP maps at the Shenhua CCS demonstration project. (**a**) Caprock interval at about 950 m depth: the 2011, 2013 and 2014 surveys (upper row) and the corresponding difference maps (lower row). (**b**) Injection interval at about 2350 m depth: same layout.

(2) Wellbore monitoring: self-developed equipment and continuous in-situ measurement. The project independently developed a downhole temperature and pressure monitoring device with intellectual property rights; after a patented automatic correction system was applied, the maximum drift error fell from 2.17% to 0.26%, and downhole pressure and equipment status are recorded every 2 h and transmitted in real time to the administration building. A permanent downhole electronic pressure gauge was also developed, providing continuous data support for injectivity assessment and stored-volume accounting [68].

(3) Near-surface and atmospheric monitoring: multi-indicator background comparison and leak discrimination. The project independently developed an in-situ CO_2 flux monitoring system at 10 m depth to reduce the systematic error of conventional surface measurement methods; the recorded variation was −0.01 to 0.01 mg/(m²·h), essentially zero, and it serves as a stability check on the downhole installation rather than as a surface flux. Surface soil CO_2 flux ranged from −160 to 680 mg/(m²·h) and the eddy-covariance CO_2 flux at 5 and 10 m height from −720 to 720 mg/(m²·h) (Figure 14) [68,79]. Background values reported for comparable local ecosystems are 150–680 mg/(m²·h) for soil flux and −800 to 300 mg/(m²·h) for eddy covariance; the measured ranges overlap these intervals but are not contained within them. The soil-flux range extends 310 mg/(m²·h) below the

lower bound, towards net uptake, whereas a CO_2 release increases the surface flux, so excursions in this direction do not indicate leakage. The eddy-covariance range exceeds the upper bound by 420 mg/(m^2·h), towards net emission, which is the direction in which a release would act and the one tested by the independent checks described below. Because the quoted intervals are single ranges from comparable ecosystems rather than multi-season envelopes for this site, the comparison is also made against values measured at the same site across seasons and at control locations; an anomaly is accepted only when it exceeds the background on successive sampling rounds and is reproduced in an independent medium—soil flux, carbon-isotope composition, groundwater chemistry, or SF_6 [80]. For atmospheric monitoring, the project established a multi-point continuous atmospheric CO_2 concentration monitoring system and carried out long-term observation, providing high-temporal-resolution data for near-surface leak identification [79]. Near-surface CO_2 concentration monitoring was deployed within a 2 km radius around the injection well covering at least 10 km^2, following the risk-graded point-layout principles for leak monitoring [81]; water samples from dozens of shallow wells showed normal groundwater quality; radar surface deformation monitoring covered 400 km^2 and showed results comparable to the unaffected background area.

Leak identification at this site did not rest on the CO_2 indicators alone (Section 4.4). SF_6 was used as a tracer, and because its natural background concentration is zero, a release to the surface is identifiable independently of the ecosystem carbon exchange [71]; no SF_6 was detected during monitoring. The detection capability of the near-surface arrays was estimated, not measured in the field, from controlled-release experiments in which leaks of 5, 8 and 10 L/min were released under wind speeds of 1–4.5 m/s; a release of 5 L/min, equivalent to about 5 t/yr, raised the CO_2 concentration 1.2 m downwind by several hundred ppm, well above instrument resolution. These experiments were conducted indoors: no controlled release was performed on site, and the site-specific detection threshold has therefore not been validated under field conditions. The value of about 5 t/yr is an order-of-magnitude estimate of the smallest resolvable release rather than a site-qualified threshold, and it bounds the sensitivity of the statements about leakage made in this paper. Simulated leakage experiments further defined the effect thresholds of CO_2 on crops such as maize (tolerance 0–500 g/(m^2·d), mortality 2000 g/(m^2·d)) [5,68].



Figure 14. Eddy-covariance CO_2 flux monitoring facility of the Shenhua CCS demonstration project.

4.4. Safety Assessment System, Long-Term Prediction, and Monitoring Performance

Regarding safety assessment, the project established a safety grading system based on five indicator groups—groundwater chemistry (pH and hardness), CO_2 flux and concentration, SF_6 concentration, surface deformation, and the vertical migration distance from VSP—assigning storage safety to five levels from I (very safe) to V (very unsafe). The grade limits are not arbitrary: the CO_2-flux grades divide the interval between zero and

the flux at which maize dies (2000 g/(m²·d), i.e., 80,000 mg/(m²·h)) into five equal parts, and the deformation limits follow the maximum uplift observed at In Salah. Indicator levels are normalized and combined with analytic hierarchy process (AHP) weights (consistency ratio 0.0476) into a single safety index; a 2014 trial gave 0.834, level I, and the post-injection index indicated that storage was in a safe state [71]. On this basis, an environmental monitoring and assessment system for CO_2 geological storage projects was developed, providing a methodological framework for the institutionalization of environmental monitoring and assessment of storage projects in China [5]. The project also established a short-term safety risk assessment method suited to the characteristics of deep saline-aquifer storage and applied it in engineering practice [74]. After injection ceased, the project continued post-injection monitoring for more than two years and, integrating geological and monitoring data, carried out numerical simulation to predict the long-term migration and saturation distribution of 302,000 t of CO_2; subsequent studies systematically analyzed plume evolution and reservoir–caprock integrity at the site, and the conclusions support the long-term stability of the storage complex [70,82].

Throughout the observation period, monitoring results at the subsurface, near-surface and atmospheric levels showed no sustained excursion beyond the local background envelope, so that no leakage was detected in any monitored domain within the detection capability of the deployed arrays. Economically, the construction capital expenditure of the demonstration project was approximately RMB 210 million (≈USD 31 million) (2010 budget, design capacity 100,000 t/a) [83]. The full-chain cost, including depreciation, labor and power, was approximately RMB 280/t (≈USD 41/t) of CO_2, of which about RMB 200/t (≈USD 30/t) was attributable to capture, transport, and injection combined and RMB 80/t (≈USD 12/t) to storage [84]. The monitoring sub-project accounted for RMB 20.91 million (≈USD 3.1 million), or about RMB 69/t stored (≈USD 10/t). The core equipment—including the self-developed downhole temperature/pressure monitoring device and the in situ CO_2 flux monitoring system at 10 m depth—was independently developed by the project, and its depreciation and maintenance are included in the monitoring sub-project budget [68] (Table 3).

Table 3. Composition and main monitoring results of the monitoring system of the Shenhua CCS demonstration project (compiled after Refs. [2,60–62]).

Monitoring Level	Monitoring Content and Means	Main Results
Atmosphere	Eddy-covariance CO_2 flux (5 and 10 m towers); multi-point continuous atmospheric CO_2 concentration	Flux about −720 to 720 mg/(m²·h), overlapping the regional background range; no anomalous increase in concentration
Near-surface	In situ CO_2 flux at 10 m depth; soil CO_2 flux; shallow groundwater chemistry	In situ flux −0.01 to 0.01 mg/(m²·h); soil flux overlapping the background range; groundwater quality normal
Surface deformation	Radar (InSAR) surface deformation monitoring (400 km²)	Comparable to the unaffected background area; no leakage-related deformation
Subsurface (reservoir/caprock)	Three time-lapse VSP surveys; continuous downhole pressure/temperature monitoring	CO_2 migration range expanded from 350 m to 450 m; no wavefield anomaly in the caprock interval; pressure decreased from 13 MPa to 5.2 MPa (permeability increasing during injection)
Wellbore system	Self-developed downhole pressure/temperature device and permanent electronic pressure gauge	Drift error reduced from 2.17% to 0.26%; continuous in situ data transmitted in real time
Integrated platform	Monitoring–safety assessment–leakage early-warning and response platform	Online integration of multi-source data; automatic safety grading and early warning

4.5. Summary: Positioning of the Shenhua Monitoring System from the Four-Dimensional Perspective

Following the four-dimensional framework of Section 1.4, the Shenhua CCS monitoring route can be attributed as follows. Storage type—a full-chain demonstration in a continental deep saline aquifer—determined that plume monitoring would rely mainly on seismic methods. Geological conditions—the low-porosity, low-permeability reservoir, the limited impedance contrast, the gently dipping structure with poorly developed faults, and the small onshore site—made repeated large-scale 3D/4D seismic surveys cost-ineffective, whereas the high-resolution near-well time-lapse VSP became the most cost-effective means of plume tracking; the dynamic injectivity evolution of "permeability increasing during injection" is likewise rooted in the water–rock reactions characteristic of a low-permeability reservoir. Regulatory context—the absence of dedicated regulations and standards for storage monitoring during the implementation period (2011–2015)—left the project to build its own "baseline first + multi-indicator mutual verification" monitoring and assessment system on the basis of general specifications such as environmental assessment technical guidelines. Project stage—a demonstration-validation period whose primary objective was "proving safety and verifying technical feasibility"—gave monitoring a "comprehensive multi-domain coverage, verification-oriented" form, which then shifted to a post-injection stage focused on long-term safety assessment after injection ceased.

Together, the four dimensions shaped the economically appropriate monitoring paradigm of Shenhua—"time-lapse VSP + downhole pressure/temperature + multi-indicator near-surface monitoring". It is both a reasonable choice under site constraints and consistent with the objectives of the demonstration stage; its limitations and upgrading directions are discussed in Section 5 along uniform comparison dimensions.

5. Comparison and Discussion of the Monitoring Systems of Typical International Projects and Shenhua CCS

This section follows the framework established in Section 1.4. It first compares the formation mechanisms of the two categories of systems from the four-dimensional perspective of "storage type—geological conditions—regulatory context—project stage" (Sections 5.1 and 5.2), answering "why the technical route is what it is"; it then compares them item by item against the six program design principles summarized in this paper, covering monitoring intensity and frequency (5.3), well and facility strategy (5.4), data management and closure (5.5), and cost and regulation (5.6), answering "whether the system design is complete"; finally it draws the implications for China (5.7). The same section presents the comparison matrix across eleven dimensions.

5.1. Comparison of System Architecture and Design Paradigm

From the perspective of regulatory context and project stage, advanced international projects generally follow a risk-driven logic of "risk analysis—monitoring requirements—technology selection—response planning" (the CRA process at Northern Lights being a typical example), with external constraints from regulations and standards such as the EU CCS Directive 2009/31/EC [85], the US EPA Class VI well requirements [20] and ISO 27914:2017 [19,86]. As a demonstration-phase project, Shenhua CCS organized multi-domain "atmosphere–surface–subsurface" monitoring mainly around technical verification and safety demonstration, in the absence of dedicated storage monitoring regulations—a typical "demonstration-verification orientation". This difference is closely related to the project's stage of development (research demonstration versus commercial operation) and regulatory environment (absence of standards during the implementation period versus

a complete regulatory framework). It does not imply a difference in capability, but the transition to commercialization will require an upgrade of the paradigm from "technology verification" to "risk-assessment driven".

5.2. Differences in Core Technical Routes and Their Causes

From the perspective of storage type and geological conditions, the international offshore saline-aquifer projects (Sleipner, Northern Lights, and Tomakomai) take 4D seismic as the core of plume imaging, whereas onshore projects each have their own strengths (InSAR at In Salah, permanent ERT at Ketzin, and combined VSP and microseismic at Decatur/IBDP); Shenhua CCS, by contrast, has formed the technical combination of "time-lapse VSP + downhole pressure/temperature + multi-indicator near-surface monitoring".

This difference can be explained from four aspects. The first is geological conditions. At Sleipner the reservoir is shallow (about 1000 m), highly porous and permeable (porosity 35–40%), and has a large CO_2–brine impedance contrast, giving excellent seismic imaging conditions. At Shenhua the reservoir is deeply buried and has low porosity and permeability, the impedance contrast is limited, and the onshore small-scale injection makes repeated large-scale 3D seismic cost-ineffective, whereas near-well high-resolution VSP is better suited to characterizing the local plume and caprock integrity. The second is injection scale and site dimensions. International commercial projects have cumulative injection at the megaton scale and plumes extending several kilometers laterally, requiring kilometer-scale surface seismic or InSAR coverage; Shenhua injected about 0.3 Mt with a plume radius of a few hundred meters, and two monitoring wells at 31.6–70 m spacing are sufficient to support spatial calibration of borehole methods. The VSP geometry is therefore scale-matched to the site: with observation wells 31.6–70 m from the injector it resolves the plume within the migration range actually imaged (350–450 m), whereas the plume at Sleipner, mapped by surface seismic, extends several kilometers [18,31]. The third is cost constraints. Although monitoring cost is low relative to capture and injection investment, it is sensitive in terms of the full-chain cost—about RMB 280/t (≈USD 41/t) on a demonstration basis, of which storage accounts for about RMB 80/t (≈USD 12/t)—so the project chose a route of using self-developed equipment to reduce long-term operating costs [68]. The fourth is regulatory and data requirements. A demonstration project's primary objective is to prove safety, without the obligation of strict quantitative verification required by carbon credit accounting, so the demand for field-wide high-precision 4D imaging is relatively weak.

In terms of technology readiness level (TRL), the backbone technologies of the Shenhua system—downhole pressure/temperature (TRL 5–6), geophysical logging (5–6), soil gas and flux (5–6), and eddy covariance (5–6)—are all high-maturity technologies, consistent with the judgement in [7] that such technologies are better suited to large commercial projects. Its seismic method is VSP (TRL 4–5), whereas international practice relies mainly on 3D/4D surface seismic (TRL 5–6); this difference is precisely the technology-readiness expression of the gap in "field-wide high-resolution imaging capability" [7,77].

The four factors do not act in parallel but occupy four different levels. Geological conditions determine whether an individual technology is effective (the feasibility level); storage type determines the macro preference of the technology portfolio (the selection level); regulatory context determines the strength of obligations and the rigidity of the program (the constraint level); and project stage determines the intensity of investment and the pace of portfolio evolution (the pacing level). When the factors conflict, regulatory requirements constitute a hard constraint—the MRV obligations of US EPA Class VI and the whole-life-cycle coverage of the EU storage directive are not waived because of favorable site conditions—whereas geological conditions define the boundary of technology choice, as a low-porosity, low-permeability reservoir cannot copy Sleipner's high-

precision route of resolving meter-scale accumulations with time-lapse seismic. The Shenhua monitoring system is precisely the result of a combination dominated by geological and economic constraints with an absence of regulatory constraints: this both explains the rationality of its technology choices and indicates the shortcomings that must be addressed at the commercialization stage.

5.3. Comparison of Monitoring Intensity and Frequency

Monitoring intensity is the direct expression of whether a monitoring system is actually implemented. Measured against the injection-period and post-closure frequency benchmarks adopted in this paper (every 1–2 years in the high-risk period and every 3–5 years in the stable period; quarterly to semi-annual for shallow groundwater; gridded by risk level for soil gas; the frequency design follows the risk-oriented framework of [7]). The basis of each interval is set out in the note to Table 4**.** Shenhua CCS and the typical international projects show a divergence of "continuous parameters meeting the benchmark while repeated geophysics is weaker". Shenhua meets or exceeds the benchmark for downhole pressure/temperature (recorded every 2 h and transmitted in real time) and near-surface flux monitoring, but in repeat geophysical acquisition it completed only three VSP surveys (2011, 2013, and 2014), neither maintaining the "every 1–2 years" repeat rate of the high-risk period nor conducting repeated 3D seismic; no public records exist for microseismic or periodic wellbore integrity testing. This divergence stems mainly from the demonstration scale (302,600 t) and cost constraints. For comparison, Sleipner, in commercial operation, completed about 10 3D seismic and four time-lapse gravity surveys during 1994–2016, Tomakomai completed five seismic surveys from injection to post-injection, and IBDP maintained high-frequency constraints through 18 months of background microseismic monitoring and annual-scale RST logging [7,31,37,41,48] (Table 4).

Table 4. Comparison of monitoring intensity and frequency between the Shenhua CCS demonstration project and typical international projects.

Monitoring Item	Practice in Typical International Projects	Practice at Shenhua CCS	Benchmark Adopted in This Paper	Comparison Conclusion
Time-lapse 3D seismic	Sleipner: about 10 surveys, 1994–2016; Tomakomai: 5 surveys from injection to post-injection (Japanese fiscal years 2016–2020)	No repeated 3D seismic	Every 1–2 years in the high-risk period and every 3–5 years in the stable period	Lack of routine field-wide imaging
VSP/cross-well seismic	IBDP: annual 3D VSP; Otway: near-continuous multi-well 4D DAS VSP	3 surveys (2011, 2013 and 2014)	Every 1–2 years (high risk)/3–5 years	Frequency below the benchmark
Downhole pressure/temperature	Continuous in most projects; continuous at IBDP and Ketzin	Continuous (recorded every 2 h and transmitted in real time)	Continuous (real time)	Meets the benchmark
Wellbore integrity	IBDP/ICCS: annual mechanical-integrity testing and pulsed-neutron logging; Weyburn: graded assessment across 177 wells	Self-developed pressure/temperature device and permanent pressure gauge; no periodic integrity testing system evident	Annually	Not documented
Microseismic	Tomakomai: continuous OBC/OBS plus Hi-net; IBDP: 18 months of pre-injection baseline plus continuous monitoring during injection	No public records	Continuous (priority in faulted areas)	Faults poorly developed at the site, a defensible trade-off

Shallow groundwater	IBDP: quarterly for years 1–2 after baseline, then semi-annual for years 3–5; Ketzin: periodic sampling at 35/55 m	Periodic sampling from dozens of shallow wells (frequency not public)	Quarterly, then semi-annual	Frequency to be clarified
Soil gas/flux	IBDP: continuous DTS plus periodic flux; Cranfield: systematic grid	In-situ 10 m flux system plus periodic soil flux monitoring	Quarterly, then semi-annual to annual	Basically meets the benchmark
InSAR deformation	In Salah: continuous observation, 2004–2009	Radar deformation monitoring covering 400 km² (staged)	Triggered/periodic	Insufficient periodicity
Post-closure monitoring	In Salah, Nagaoka and Ketzin: long-term post-injection monitoring; Cranfield: 3 years after injection	Continuous monitoring for more than 2 years after injection ceased, with numerical prediction	Continuous pressure; seismic every 5–10 years or triggered; groundwater annually	Comparable to the benchmark

Note: The benchmarks are not statutory values. Where the US EPA Class VI rule prescribes an interval, that value is adopted: continuous recording of injection pressure, rate and annulus pressure, mechanical-integrity testing at least annually, corrosion monitoring quarterly, and pressure fall-off testing and plan review at least every five years [20]. The rule does not fix the frequency of seismic, groundwater or soil-gas surveys, so the intervals used here follow the cadence observed at the reference projects in Table 2 for seismic and groundwater, and the quarterly-to-annual range given in Ref. [7] for surface soil and atmospheric surveys. Where the two differ, the stricter interval is applied during injection and the more relaxed one after closure.

5.4. Monitoring Well and Facility Strategy

In terms of risk relevance, wellbore integrity monitoring has the highest priority in CO_2-EOR settings and a lower priority in saline aquifers, which explains the difference in facility strategy between the two categories of projects [7]. International practice tends to be cautious about dedicated monitoring wells: Northern Lights converted an existing appraisal well to meet monitoring and contingency injection needs without drilling a new deep monitoring well, while Tomakomai reflects the lesson that onshore monitoring wells are costly and functionally constrained. In March 2024, monitoring well VW2 of the ADM IL-ICCS project suffered corrosion leakage at a depth of about 1524 m (leakage revised to 2670–3940 t, with fluids entering the Ironton–Galesville Formation above the caprock), showing that even when a well is built to Class VI standards and periodically tested for integrity, the long-term risk to wellbore integrity cannot be ignored [48]. Shenhua CCS adopted a compact well layout of "one injection well + two nearby monitoring wells" (at 31.61 m and 70 m), supporting the multi-purpose use of a small number of wells for VSP, downhole pressure/temperature, and fluid sampling, which is consistent with the economics of the demonstration scale; its limitation is the limited spatial coverage of asymmetric plume extension and far-field anomalies, and megaton-scale projects should, while retaining the "few wells, multiple functions" approach, supplement it with distributed optical fiber or sparse permanent sources according to risk assessment.

The public record for Shenhua does not document a periodic integrity-testing program, and the available evidence does not distinguish between two possibilities. Testing may have formed part of routine well operations without being reported; alternatively, it may not have been formalized, since no dedicated standard for CO_2 storage well integrity applied when the wells were designed, although the injection wells were completed with surface, intermediate and injection casing, and cement returned to surface [84]. The distinction matters for benchmarking: in the first case the limitation lies in disclosure, in the second in practice. Both are addressed by the same recommendation—annual mechanical-integrity testing and cement-bond logging written into the domestic specifications now being issued.

5.5. Data Management and Monitoring–Modeling Closure

This paper regards data acquisition standards (standard operating procedures, instrument calibration chains, the three-level automatic–manual–cross review, and audit trails) as the foundation of monitoring reliability, and considers that an integrated platform should provide five functional modules—data management, reservoir simulation, history matching, risk early warning, and visualization—following the functional scope of the integrated systems reviewed in [7]. Shenhua CCS has built an information platform integrating online display of monitoring data, safety assessment, and leakage early warning, with initial capability in data integration and automatic warning [68]; its nine functional modules span map operation, data acquisition, query and statistics, early warning, dispersion simulation, safety assessment, information release, and system administration—including a dispersion-simulation module for contingency planning, but no reservoir-simulation or history-matching module. Publicly available information does not show institutionalized standard operating procedures or a data quality review system, and monitoring data are mainly used internally.

Monitoring–modeling closure is used here in the sense set by ISO 27914:2017, where the coupling is mandatory: models are refined as new data are acquired (5.5.2.1), operational data feed flow models (8.5.1), and M&V activities calibrate predicted performance, with monitoring practices "evaluated and adapted during the course of injection" (9.2.3) against pre-defined metrics (9.4.1) [19,87]. Four requirements follow—data constrain the model, calibration is reported, model and monitoring program are iterated during injection, and the outcome feeds back into monitoring scope or operations. The reviewed projects sit at different points along this sequence: Ketzin updated its static and dynamic models regularly as data accumulated and reported history matching in good agreement with monitoring [62]; Aquistore obtained qualitative and quantitative agreement from a simulation calibrated against time-lapse RST data, and at AEP Mountaineer a history-matched prediction supported shortening post-injection monitoring from twenty years to about five [7]. The Sleipner experience has in turn been carried forward into the design of the Northern Lights monitoring program [34]. At Shenhua, VSP-derived migration distance and saturation were used to calibrate an ECLIPSE 300 model against downhole monitoring [82], and the calibrated model supported optimization of the later monitoring program and safety assessment. The technical sequence is thus present, but it was completed after shut-in as a research exercise: the comparison was qualitative, it recorded a discrepancy between model and seismic prediction in the layer showing the farthest migration, and no re-calibration followed. ISO 27914:2017 requires monitoring practices to be evaluated and adapted during injection [19], and this is the specific sense in which closure has not been institutionalized.

Accordingly, Chinese storage projects should define data standards, quality-control processes, and tiered sharing strategies at the construction stage, and couple model updating to the monitoring cycle from the start of injection, so that monitoring data can become comparable across projects and acceptable to regulators [7,17].

5.6. Cost and Regulation

Monitoring cost scales with project size and stage and depends on the boundary of the estimate (Table 5). For the Shenhua demonstration, four metrics are reported separately—a one-off capital outlay, a per-ton full-chain cost, a storage-only cost, and a monitoring-only cost—in Section 4.4 and, with their boundaries, in Table 5. Across the ten projects, unit costs differ by an order of magnitude, mainly reflecting differences in scale (0.3 Mt at Shenhua and Tomakomai versus 20–30 Mt at Sleipner and Weyburn) and in cost boundary [7].

Monitoring-only cost can be separated for two of the eleven projects—Shenhua and Sleipner—as total monitoring expenditure divided by the CO_2 stored over the same period; for the other eight the sources reviewed report a project budget or an injection cost without a separate monitoring line. At Shenhua the sub-project on monitoring, safety assessment and early-warning technology was budgeted at RMB 20.91 million, equivalent to about RMB 69/t stored (≈USD 10/t) and to about 10% of the capital investment. At Sleipner, ten 4D seismic surveys, four gravity surveys and supporting seabed and water-column sampling between 1996 and 2018 cost an estimated €42 million, equivalent to about €2/t (≈USD 2.2/t) [7]; the estimate excludes technical and administrative support, whereas the Shenhua figure includes instrument development, depreciation, and safety assessment. Monitoring cost per ton is therefore about 4.5 times higher at Shenhua, against a tenfold difference in annual injection rate (about 0.1 Mt/yr and about 1 Mt/yr); IEAGHG reports that unit monitoring cost falls with throughput and converges at USD 1–4 million per year (USD 1–4/t at 1 Mt/yr) for projects of about 1 Mt/yr [7].

In terms of regulation, international projects generally operate within a clear regulatory framework (the Norwegian Petroleum Act and pollution control regulations, US EPA Class VI and Subpart RR [20], the EU storage directive 2009/31/EC [85], ISO 27914:2017 [19] and ISO 27916:2019 [88]), with monitoring programs, detection thresholds, and closure criteria all having a legal basis [9,19]. During the Shenhua demonstration period. no dedicated storage monitoring regulations or standards existed in China, and the project built a "baseline first + multi-indicator mutual verification" monitoring and assessment system on the basis of general documents such as the specification for leakage risk assessment of CO_2 geological utilization and storage projects [5]. Since 2023, China has successively issued national and industry standards including GB/T 46878-2025 (identical to ISO 27914:2017), GB/T 46559-2025, and SY/T 7785-2024 [87,89,90], so that site assessment, environmental risk control, and CO_2 detection now have rules to follow [86]. Nevertheless, dedicated specifications for monitoring frequency, data quality control, and detection thresholds remain incomplete, and the experience of the existing standards is not yet a substitute for binding monitoring technical specifications. ISO/TR 27923:2022 and PD ISO/TR 27926:2024 provide technical guidance on injection operations, infrastructure and monitoring, and on the transition from EOR to storage, respectively [91,92]; the standards system for offshore storage is also under construction [93]. Internationally, the application of ISO standards to geological storage and EOR has likewise been systematically reviewed [94].

Table 5. Comparison of cost metrics and basis between the Shenhua CCS demonstration project and typical international projects.

Project	Total Stored	Cost Metric	Cost Boundary	Value	Source
Shenhua CCS	302,600 t	Construction capital expenditure (CAPEX)	Full chain (capture + 13–15 km transport + injection + monitoring); capex, 2010; design 0.1 Mt/yr	≈RMB 210 million (≈USD 31 million)	[83]
Shenhua CCS	302,600 t	Full-chain cost (incl. depreciation)	Capture + transport + storage; incl. depreciation, labor, and power	≈RMB 280/t (≈USD 41/t; capture/transport/injection ≈RMB 200 + storage ≈RMB 80)	[84]
Shenhua CCS	—	Storage-only cost	Storage only (excl. capture and transport)	≈RMB 80/t (≈USD 12/t)	[84]
Shenhua CCS	302,600 t	Monitoring sub-project	Monitoring & safety assessment only	RMB 20.91 million (≈RMB 69/t; ≈USD 3.1 million, ≈USD 10/t)	Project budget/acceptance
Ref.: Taizhou (coal power)	—	Capture cost	Capture only (excl. transport and storage)	≈RMB 208/t (≈USD 29/t)	[95]

Sleipner	≈20 Mt	Levelized abatement cost	Full chain; capture at site (0 km transport); incl. monitoring; excl. carbon-tax credit	≈RMB 120/t (≈USD 17/t)	[96]
Sleipner	≈20 Mt	Monitoring-only cost	Monitoring only (10 4D seismic surveys, 4 gravity surveys, seabed and water-column sampling, wellhead metering), 1996–2018; excludes technical and administrative support	≈€42 million; ≈€2/t (≈USD 2.2/t)	[7]
Weyburn–Midale	>30 Mt	Net CO_2 cost	Injection + 315 km pipeline transport; net of incremental oil revenue	≈USD 20/t (≈RMB 166/t)	[97]
Tomakomai	≈0.3 Mt	Full-chain cost	Capture + 1.4 km transport + storage; incl. monitoring; government-funded (excl. commercial return)	>JPY 10,000/t (≈USD 92/t; ≈RMB 633/t); capex ≈JPY 30 bn (≈USD 275 million; ≈RMB 1.9 bn)	[98]
In Salah	≈3.8 Mt	Unit injection cost	Injection only; excl. 14 km transport	≈USD 6/t (≈RMB 44/t)	Compiled

5.7. Gap Identification and Implications for China

For Shenhua CCS, coverage is uneven across domains (Figure 15; Table A1): every item is recorded in the near-surface and atmospheric domains, giving full coverage in both and matching the highest of the projects compared. No repeat 3D seismic was acquired, so the reservoir domain stands at 67%, the same as most other projects; nine of the ten international projects have at least a baseline 3D survey. No integrity logging is documented, leaving the wellbore domain at 50%. The cross-cutting attributes reach 17% (Table A1): monitoring-to-model feedback, data sharing, and standards compliance are not in place. The verification-oriented design paradigm, the absence of dedicated domestic specifications, and the limited localization of equipment underlie these deficits [17,68].

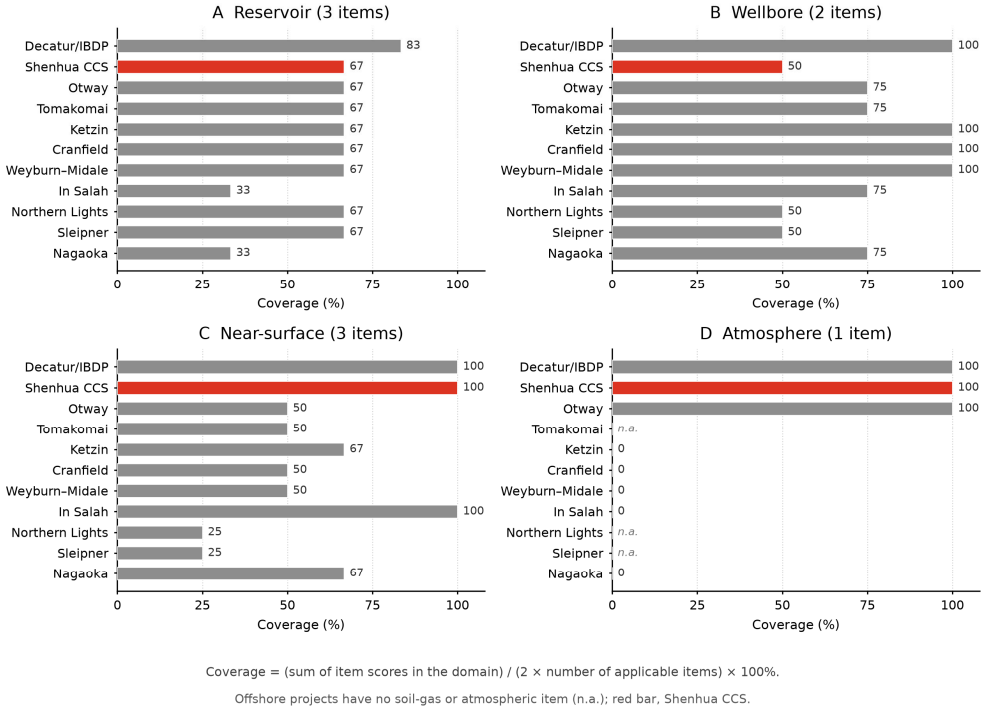


Figure 15. Documented-technology coverage in the four monitoring domains for the eleven projects. Coverage is the sum of item scores divided by twice the number of applicable items, with items coded as in Table A1; offshore projects have no soil-gas or atmospheric item. Shenhua CCS is shown in red.

Taking the six program design principles summarized in this paper (risk orientation, whole-life-cycle coverage, dynamic adaptation, multi-level integration, regulatory compliance, and monitoring–modeling closure) as a reference, the improvement directions for megaton-scale projects can be defined:

For risk orientation, complete features, events, and processes (FEPs) analysis and risk registers during site characterization and write detection thresholds and response plans into the monitoring program. For whole-life-cycle coverage, complete environmental baseline surveys covering all four seasons before injection, and after closure execute pressure monitoring continuously, seismic surveys every 5–10 years or on a triggered basis, and groundwater monitoring annually. For dynamic adaptation, establish an annual program review, and streamlining mechanism that actively narrows the monitoring portfolio as risk declines. For multi-level integration, configure the onshore saline-aquifer portfolio in three tiers: sparse surface 3D/4D seismic for field-wide plume extent, borehole VSP or DAS for near-well calibration and model updating, and downhole pressure with InSAR and a near-surface network for continuous verification, avoiding reliance on a single technical route [7]. Therefore, the composition of the portfolio, not only its density, changes with project scale. For regulatory compliance, benchmark against ISO 27914:2017 [19], the EU directive [85] and EPA Class VI [20], and, building on the already issued standards such as GB/T 46878-2025 and SY/T 7785-2024 [87,89], refine the requirements for monitoring frequency, data quality control, and detection thresholds, while promoting the establishment of standards for the construction and management of shallow groundwater monitoring wells [17]. For monitoring–modeling closure, deploy data standards, quality-control processes, and an integrated platform simultaneously at the construction stage, and incorporate history matching and early warning into routine operations [7].

At the same time, technologies such as integrated "space–air–ground–well" systems, IoT-based online monitoring, and artificial-intelligence anomaly detection are maturing rapidly, providing realistic conditions for China's monitoring system to achieve a technological leap [4,16]. Table 6 compares the Shenhua CCS demonstration project with typical international projects across 11 dimensions—project positioning, injection scale, reservoir and geological conditions, design paradigm, regulatory basis, core technology portfolio, well strategy, monitoring–modeling closure, data sharing, equipment and platform, and cost magnitude. The largest differences lie in three areas: the design paradigm (demonstration-verification orientation versus risk-driven), the core technology portfolio (time-lapse VSP + downhole pressure/temperature + multi-indicator near-surface monitoring versus 4D seismic as the core supplemented by InSAR/ERT/microseismic/gravity), and institutional support (absence of regulatory basis, data sharing and monitoring–modeling closure versus the EU directive, EPA Class VI, ISO 27914 and open mechanisms such as the benchmark model and CO2DataShare). Among these, project positioning, injection scale, and reservoir/geological conditions are inherent and underlie all subsequent technological differences, whereas cost magnitude reflects scale effects and differing cost bases and should not be used to judge system merits (Section 5.6).

Table 6. Multi-dimensional comparison of monitoring systems between the Shenhua CCS demonstration project and typical international CCS projects (compiled in this work).

Comparison Dimension	Shenhua Ordos CCS Demonstration Project	Typical International Projects (Mainstream Practice)
Project positioning	National research demonstration (full chain)	Mainly commercial operation, with research pilots secondary
Injection scale	About 0.3 Mt (2011–2015)	Sleipner about 20 Mt, etc. (megaton scale)
Reservoir/geology	Low-porosity, low-permeability continental saline aquifer (below 1600 m)	Mainly high-porosity, high-permeability marine sandstone (in most cases)

Design paradigm	Demonstration-verification orientation (multi-domain coverage)	Risk (CRA) driven, whole life cycle
Regulatory basis	No dedicated domestic storage monitoring regulation (absence of standards)	EU directive/EPA Class VI/ISO standards
Core technology portfolio	Time-lapse VSP + downhole pressure/temperature + multi-indicator near-surface	4D seismic as the core plus InSAR/ERT/microseismic/gravity, etc.
Well strategy	1 injection and 2 monitoring wells (compact, closely spaced)	Diverse: conversion of existing wells and hierarchical decisions on dedicated wells
Monitoring–modeling closure	Initially established (prediction after injection ceased)	Institutionalized closure and benchmark models established
Data sharing	Not yet open	Sleipner benchmark model, CO2DataShare, etc.
Equipment and platform	Self-developed pressure/temperature device, in situ flux system, early-warning platform	Commercial equipment such as DAS/DTS and permanent ocean-bottom seismometers
Cost magnitude	Total investment about RMB 210 million (about RMB 280/t full-chain); monitoring sub-project about RMB 69/t (≈USD 10/t)	Monitoring-only cost about €2/t at Sleipner (≈USD 2.2/t); a small share of project budgets [7]

The pathway–tool mapping of Section 2.3.2 becomes an ordered choice once the geological setting is fixed. Table 7 sets out, for the four settings examined in this paper, which technologies carry the routine burden, which are acquired on a periodic schedule, and which are triggered by an anomaly. The ordering follows the cost–information trade-off of Section 2.3.4: technologies that constrain the dominant pathway continuously at low marginal cost are placed first, and high-cost acquisitions are scheduled against risk—the principle by which the largest single item in the Sleipner monitoring budget, 4D seismic at about 95% of the total, is managed [7].

Table 7. Ordering of monitoring technologies by geological setting and dominant leakage pathway.

Geological Setting and Cases	Dominant Leakage Pathway	Routine (Continuous or Automated)	Periodic (Scheduled)	Triggered (Anomaly- or Milestone-Driven)
Offshore high-permeability saline aquifer (Sleipner, Northern Lights, Tomakomai)	Plume migration beyond the licensed area; seabed leakage	Downhole pressure and temperature	Repeat 3D/4D seismic; seabed environmental surveys	Gravity and CSEM; water-column chemistry and bubble-flow acoustics
Onshore low-permeability continental aquifer (Shenhua)	Caprock and fault leakage; wellbore; shallow hydrological	Downhole pressure and temperature	InSAR; soil-gas and shallow-groundwater grid; VSP or DAS for near-well calibration	Field-wide 3D/4D seismic, scheduled against risk
Depleted reservoir or CO_2-EOR field with legacy wells (Weyburn–Midale, Cranfield)	Wellbore integrity	Annulus and wellhead pressure	Integrity logging; tracer tests	Repeat seismic for conformance
Fault- or fracture-dominated setting (In Salah)	Fault reactivation; cross-fault migration	Microseismic; downhole pressure and temperature	InSAR	Caprock-interval VSP; above-zone pressure

6. Conclusions and Outlook

6.1. Main Conclusions

The following conclusions respond in turn to the three questions raised in the Introduction.

(1) Differences in monitoring technical routes are jointly determined by four factors. Storage type determines the macro preference (saline aquifers center on seismic imaging, whereas CO_2-EOR centers on wellbore integrity and geochemistry); geological conditions determine the effectiveness of individual technologies (the time-lapse seismic at Sleipner and the InSAR at In Salah both presuppose specific site conditions); and regulatory context and project stage determine the intensity of monitoring and the strength of obligations (the CRA loop under the Norwegian Petroleum Act, the life-cycle MRV of EPA Class VI and Subpart RR, and the technology-verification orientation of pilot projects) [7,9,19]. No universally applicable monitoring scheme can therefore be transplanted from one site to another.

(2) Shenhua CCS is a reasonable but still incomplete choice under the triple constraints of "demonstration stage, low-porosity low-permeability continental saline aquifer, and absence of domestic standards at the time". Its reasonableness is reflected in the following: through three time-lapse VSP surveys (migration range within the injection interval expanding from 350 m to 450 m, with no wavefield anomaly observed in the caprock interval at 950 m depth), self-developed downhole pressure/temperature devices (drift error reduced from 2.17% to 0.26%), and multi-indicator near-surface monitoring (in situ flux variation essentially zero; surface and eddy-covariance fluxes overlapping the regional background ranges), no leakage was detected across multiple domains within an injected volume of 302,600 t; and the construction capital expenditure of approximately RMB 210 million (≈USD 31 million), of which the monitoring sub-project accounted for RMB 20.91 million (≈USD 3.1 million; about RMB 69/t stored, ≈USD 10/t), is commensurate with the scale of a 0.3 Mt demonstration [68,71]. At Sleipner, the monitoring-only cost is about €2/t (≈USD 2.2/t) [7]. The full-chain cost was about RMB 280/t (≈USD 41/t), of which storage accounted for about RMB 80/t (≈USD 12/t) [84]. Its incompleteness lies in the following: the design paradigm is still technology-verification oriented and has not yet completed the transition to risk-assessment driven; the large-scale application of high-resolution geophysics is insufficient (repeated 3D and routine 4D seismic are lacking); mechanisms for data standardization, quality control, and open sharing are absent and monitoring–modeling closure has not been institutionalized; and the technical specifications for storage monitoring and the degree of equipment localization need improvement. Domain coverage (Figure 15) is full in near-surface and atmospheric monitoring but lowest in the cross-cutting attributes.

(3) For megaton-scale projects, the monitoring system should be built along the pathway of "risk-based hierarchical design + low-cost high-value technology portfolios + monitoring–modeling closure + standards first + data sharing": starting from site risk assessment to define monitoring objectives and detection thresholds; giving priority to low-cost, high-information technologies such as distributed optical fiber (DAS/DTS), InSAR, and downhole/surface ERT; and arranging repeat acquisition of time-lapse seismic on a tiered basis [7,16,17]. Borehole VSP cannot substitute for this field-wide coverage: it resolves the reservoir only near the well and serves calibration and model updating rather than plume delineation. Monitoring wells possess the dual attributes of observation window and potential leakage pathway, so dedicated monitoring wells should be decided hierarchically according to risk assessment, with low-risk sites giving priority to the scheme of "multi-purpose use of injection wells + surface and near-surface combinations" [48].

6.2. Outlook

A megaton-scale project stores nearly two orders of magnitude more CO_2 than the 0.30 Mt injected at Shenhua, and for a reservoir of comparable thickness the lateral extent of the plume grows roughly with the square root of the stored volume, from a few hundred meters to several kilometers. The fraction of the plume that borehole methods can

resolve falls accordingly, which is why field-wide seismic and InSAR take the primary role at that scale. The pathway proposed above is drawn from projects already operating at 1–1.5 Mt/a—Sleipner since 1996 and Northern Lights. The comparison concerns monitoring system design; coupled flow and geomechanical simulation are outside its scope, and the pathway is a design framework, not a quantitative prediction. For large-scale deployment, four areas require further work. The first is the engineering validation of monitoring–modeling closure: existing conclusions derive mostly from single-point practice at pilot projects, and their stability in predicting long-term pressure and plume evolution needs to be tested in megaton-scale projects, with quantitative indicators of model confidence specified [7]. The second is the portfolio optimization of low-cost, high-information technologies: cross-site comparable data on the cost–effectiveness relationship of distributed optical fiber, permanent downhole ERT, sparse permanent sources, and InSAR are still lacking, and technology-selection criteria should be established through demonstration comparisons based on uniform metrics [16]. The third is standards and data governance: the formulation of storage monitoring technical specifications requires support from domestic project data, while the comparability of such data depends on uniform acquisition standards and quality-control processes; the two should advance in step, with interfaces reserved for international mutual recognition [9,17]. A fourth task is the field validation of detection thresholds: at Shenhua the threshold was estimated from indoor release experiments, and controlled releases at site scale are needed before a threshold can be quoted as site-specific.

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Data Availability Statement: No new datasets were created in this study. All data are taken from the sources cited in the text and are contained in this article and its Appendix A: project attributes and monitoring parameters in Table 2, with the sources identified against each project; monitoring results and frequency benchmarks in Tables 3 and 4; cost figures and their boundaries in Table 5, with the source stated for each row; and the item-by-item coding behind Figure 15 in Table A1, with the abbreviations used in Abbreviation Table. A few operational details of the Shenhua Ordos demonstration project are recorded only in the project's internal technical reports, which cannot be released for reasons of commercial confidentiality.

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Abbreviations

Abbreviations used in this paper.

Abbreviation	Full Form
ADM	Archer–Daniels–Midland Company
AEP	American Electric Power
AHP	analytic hierarchy process
AZMI	above-zone monitoring interval
BGP	Bureau of Geophysical Prospecting, China National Petroleum Corporation
CAAS	Chinese Academy of Agricultural Sciences
CAPEX	capital expenditure
CCS	carbon capture and storage
CCUS	carbon capture, utilization, and storage
CNOOC	China National Offshore Oil Corporation
CRA	containment risk assessment
CSEM	controlled-source electromagnetics
DAS	distributed acoustic sensing
DSS	distributed strain sensing
DTS	distributed temperature sensing
EOR	enhanced oil recovery
EPA	United States Environmental Protection Agency
ERT	electrical resistivity tomography
EU	European Union
FEPs	features, events, and processes
IBDP	Illinois Basin Decatur Project
IEAGHG	IEA Greenhouse Gas R&D Program
IL-ICCS	Illinois Industrial Carbon Capture and Storage project
InSAR	interferometric synthetic aperture radar
ISO	International Organization for Standardization
JCCS	Japan CCS Co., Ltd.
METI	Ministry of Economy, Trade, and Industry (Japan)
MMV	measurement, monitoring, and verification
MRV	measurement, reporting, and verification
MVA	monitoring, verification, and accounting
OBC	ocean-bottom cable
OBS	ocean-bottom seismometer
PNC	pulsed neutron capture
RITE	Research Institute of Innovative Technology for the Earth (Japan)
RST	reservoir saturation tool
SECARB	Southeast Regional Carbon Sequestration Partnership
SOV	seismic orbital vibrator
TRL	technology readiness level
VERA	vertical electrical resistivity array
VSP	vertical seismic profiling

Appendix A

Table A1. Coding of the 12 technology lines for the eleven projects. ●, deployed and documented with parameters (score 2); ○, mentioned without parameters or deployed intermittently (score 1); ×, no record in the sources cited in this review (score 0); n.a., not applicable. Compiled from Table 2, Section 3, and Ref. [18].

Item	Sleipner	Northern Lights	Toma-komai	In Salah	Deca-tur/IBDP	Nagaoka	Weyburn–Midale	Cranfield	Otway	Ketzin	Shenhua CCS
A1 Repeat 3D seismic (Reservoir)	●	●	●	●	○	×	●	●	●	●	×
A2 Borehole seismic, VSP or DAS (Reservoir)	×	×	×	×	●	●	●	●	●	●	●
A3 Continuous downhole pressure and temperature (Reservoir)	●	●	●	×	●	×	×	×	×	×	●
B1 Integrity logging or testing (Wellbore)	×	×	○	○	●	○	●	●	○	●	×
B2 Wellhead pressure and flow (Wellbore)	●	●	●	●	●	●	●	●	●	●	●
C1 Soil gas concentration or flux (Near-surface)	n.a.	n.a.	n.a.	●	●	●	●	●	●	●	●
C2 Shallow groundwater or seawater chemistry (Near-surface)	○	○	●	●	●	○	○	○	○	●	●
C3 Surface or seabed deformation (Near-surface)	×	×	×	●	●	○	×	×	×	×	●
D1 Atmospheric CO_2 concentration or eddy-covariance flux (Atmosphere)	n.a.	n.a.	n.a.	×	●	×	×	×	●	×	●
E1 Baseline completeness (Cross-cutting)	●	●	●	●	●	●	●	●	●	●	○
E2 Monitoring-to-model feedback (Cross-cutting)	○	●	○	○	○	○	○	○	●	●	×
E3 Data sharing and standards (Cross-cutting)	●	○	●	●	●	○	●	○	●	●	×

Note: Codings follow the cited sources and are in some cases more complete than the portfolios summarized in Table 2 (for example, soil-gas sampling at Ketzin). A zero indicates absence from the cited sources, not necessarily absence of the activity.

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