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Monitoring and Modelling of CO_2 Storage: The Potential for Improving the Cost-Benefit Ratio of Reducing Risk

IEA GREENHOUSE GAS R&D PROGRAMME

International Energy Agency

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MONITORNG AND MODELLING OF CO_2 STORAGE: THE POTENTIAL FOR IMPROVING THE COST-BENEFIT RATIO OF REDUCING RISK

(IEA/CON/19/255)

The study was proposed with the intention of developing an understanding of where future research efforts in CO_2 storage technologies should be focused on in the next decade, informing the potential directions for future research in order to fully maximise the potential benefits of storage technologies to commercial-scale CCS projects.

Key Messages

- Monitoring technologies in CO_2 storage provide options to address site-specific risks which may affect project performance, storage security, human health, the environment and surface features.
- Monitoring provides accountability for injected CO_2, ensures regulatory requirements are met, provides detection of leakages and assesses CO_2 migration; key criteria in a risk assessment plan.
- There are opportunities to reduce costs in monitoring, and projects may benefit from doing such analyses when planning their monitoring programmes
- There is a confidence in the range of monitoring technologies available for large-scale CO_2 storage (on the scale of ~1 Mt CO_2 per year).
- There is a large range in monitoring costs, therefore it can be hard to interpret the cost-benefit ratio.
- Commercial scale projects storing on the order of 1 Mt CO_2/year usually incur costs on monitoring alone of around US $1-4 million (per year).
- Economies of scale do exist; so the higher the volume of CO_2 to be stored, the costs per tonne do decrease.
- Monitoring costs in construction, well drilling, characterisation, administrative and technical support are fairly consistent. Monitoring costs are generally a small fraction of the whole project (less than 5% of the total costs which is significant in comparison to capital and operating costs of capture facilities), and many monitoring methods are reasonably priced.
- Pilot projects focussed on research had high costs to validate a range of technologies.
- Earlier pilot projects (i.e. those that became operational in the 1990's and early 2000's) were not subject to the same regulations as new projects, meaning simpler monitoring programmes were undertaken and therefore costs were lower.
- Analogues for CO_2 storage (such as natural CO_2 fields, offshore oil and gas operations and natural gas storage) provide monitoring examples for the evaluation of long-term monitoring.
- There is an overall confidence in the range of technologies for monitoring CO_2 storage and current operational projects have made their monitoring programmes more efficient, focussing on the most useful methods to address specific project risks and better control costs.
- The path forward for implementing the safe storage of carbon dioxide seems stable.

Background to the Study

There is a large amount of information on modelling and monitoring from conceptual studies, pilot- and full-scale operations. There is also an understanding from these projects on how and why certain monitoring plans were chosen and designed, a knowledge of the costs incurred, and evidence on why and how such projects have evolved over the storage lifecycle. This study has selected the most effective monitoring techniques in terms of cost-benefit and technical effectiveness, evaluated their impact and recommending priorities for the future.

End users intended for the report include operators of CCS projects, technology vendors, regulators, financial supporters, technical consultants, oil and gas operators, and the research community. These stakeholders all have an interest and, could either influence, or be directly involved in establishing monitoring programmes for CCS applications.

Scope of Work

The aim of this report was to select commercial-scale CCS projects to use as references and define and categorise the technologies used. The main tasks undertaken were a thorough literature review, a technology readiness level (TRL) assessment of each tool, case studies of large-scale monitoring programmes, and a cost-benefit analysis of select research and development technologies. The technologies to be looked at included a wide range of near-surface and surface, atmospheric and reservoir techniques.

The contractors used experience from CCS projects worldwide, including site screening and characterisation, reservoir modelling, operational modelling and post-injection site closure. A wide range of monitoring techniques were looked at, with emphasis on applied research and development to define the potential for improving the cost-benefit ratio to reduce project risk. As well as the literature review, this work also engaged with personnel from CO_2 storage projects by conducting interviews to gain their practical knowledge. Key messages were then ascertained around areas such as the status of monitoring techniques, storage risks, monitoring cost-benefits, monitoring of the CO_2 plume and monitoring programme operations in the storage of CO_2.

The brief, initial scoping case studies looked at In Salah, Weyburn, Nagaoka, the Frio Brine Pilot, the IEAGHG monitoring network outcomes, US DoE-NETL MMV (monitoring, measurement and verification) and accounting Best Practices Manual and the STEMM-CCS project. The summary of the technologies to be included a general description, the zones monitored, the equipment, processing requirements, frequency, domain, accuracy and resolution, TRL / field application, coverage, costs, risk category and finally the advantages and disadvantages of each. Alongside the summary table, radar plots were created which provide a pictorial summary of the cost-benefit metrics for each technology. The report includes a cost-benefit analysis for each technology.

Findings of the Study

Literature Review

There is an overwhelming extent of information on monitoring technologies available, so this study conducted refined searches specific to storage criteria and risk assessment. The majority of research on storage has been focussed on the reservoir zone, thus many of the technologies available for monitoring or characterising subsurface conditions have been adopted from the oil and gas industry. Many near surface and atmospheric technologies were adopted from the environmental or remote sensing industry. The literature data was reviewed and refined to common technologies addressing capacity, containment, injectivity, contingency, mitigation and public acceptance.

Forty three existing technologies for storage were reviewed and summarised to help illustrate the options available for monitoring CO_2 in the subsurface, plume dimensions, migration / leakage, surface operations and the environment. To provide specific cost-benefit metrics for storage monitoring technologies, the review included information on the monitored zone, equipment necessary for deploy, pre / post processing requirements, frequency of data collection, domain covered (if applicable), accuracy or resolution, technology readiness level (TRL) and field application, coverage of technology, general cost ranges, risk category, and the benefits and limitations of the technology.

A wealth of information was provided in the summary table (Table 2-3, ‘CO_2 storage monitoring technology cost benefit matrix’, pages 14-17 in the report itself). A rating system was prescribed for each aspect described for each of the 43 technologies, based on the cost-benefit of the technology and plotted on radar graphs to give a quick-look, general review of the monitoring options; see figure 1, below, for an example of the radar plots used. The below example plots demonstrate the cost-benefit metrics for some of the techniques studied for atmospheric CO_2 storage monitoring technology in particular.

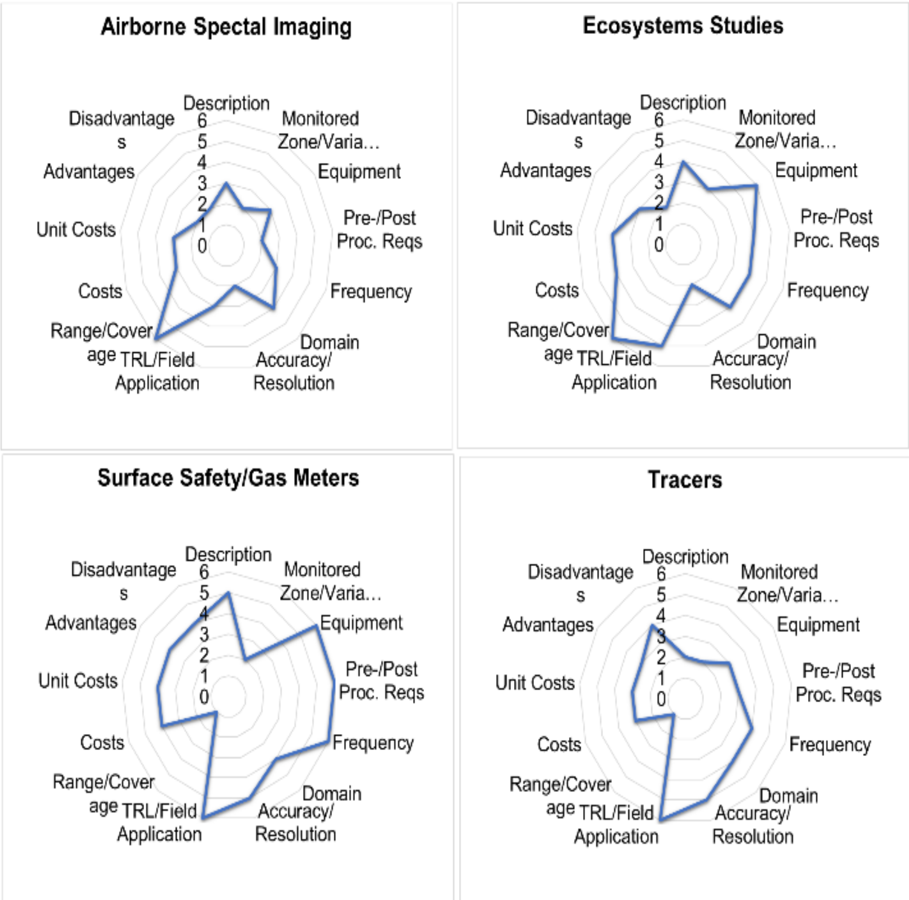

Fig 1. Example radar plots demonstrating selected atmospheric monitoring technologies

(IEA/CON/19/255, pg 21)

The radar plots are available in pages 19 to 22 of the report, and for this display of the information a low benefit rating was marked as ‘1’ and a high cost-benefit rating was a ‘6’. On these radar plots, a large circular shape means there are more overall higher cost-benefits, and a smaller circle plot means that technology leans to more specialised applications. It must be noted that ‘there is no single technology with maximum benefit and low costs’. Those that came out seemingly higher in the overall cost-benefit analysis were the annulus pressure testing, microseismic/seismic activity monitoring, casing pressure monitoring, long-term downhole pH and cement bond logs. Those technologies slightly lower on the cost-benefits included vertical seismic profiling (VSP), land EM and ERT, multicomponent surface seismic, airborne EM and spectral imaging, and bubble stream detection.

With atmospheric technologies, those rating higher for cost to benefit ratio were the non-dispersive IR gas analysers and the surface/safety gas meters. Those rating lower included airborne spectral imaging. For reservoir monitoring technologies, annulus pressure testing, casing pressure monitoring, downhole pressure-temperature and downhole pH monitoring all rated rather highly. Crosswell seismic, VSP, multicomponent surface seismic, land EM and land ERT all rated lower.

The study also reviewed the integration of monitoring with modelling, looking at several case studies and concluding that CCS projects have successfully integrated both practices to provide a competent operational performance feedback look, as improved understanding of the system in question helps to evaluated and then guide the operating and monitoring strategy.

CCS projects have tested the applicability of various monitoring technologies in the field, improving the understanding of the technical and operational considerations needed for technology implementation and improving the criteria for preferential tool selection to also satisfy regulatory requirements. Many current CCS projects have used a risk-based monitoring, verification and accounting (MVA) plan for conformance based on their lifecycle cost-benefit analysis, including the Shell QUEST project. The Boston Square approach, see figure 2, below, has also been used to qualitatively evaluate the perceived cost-benefit of the specified technologies in some case studies, and the IEAGHG on-line monitoring selection tool is another application that identifies and evaluates suitable methods for a given project and site characteristics, using an extensive library of case studies to provide a huge knowledge base of experience in the monitoring of CO_2.

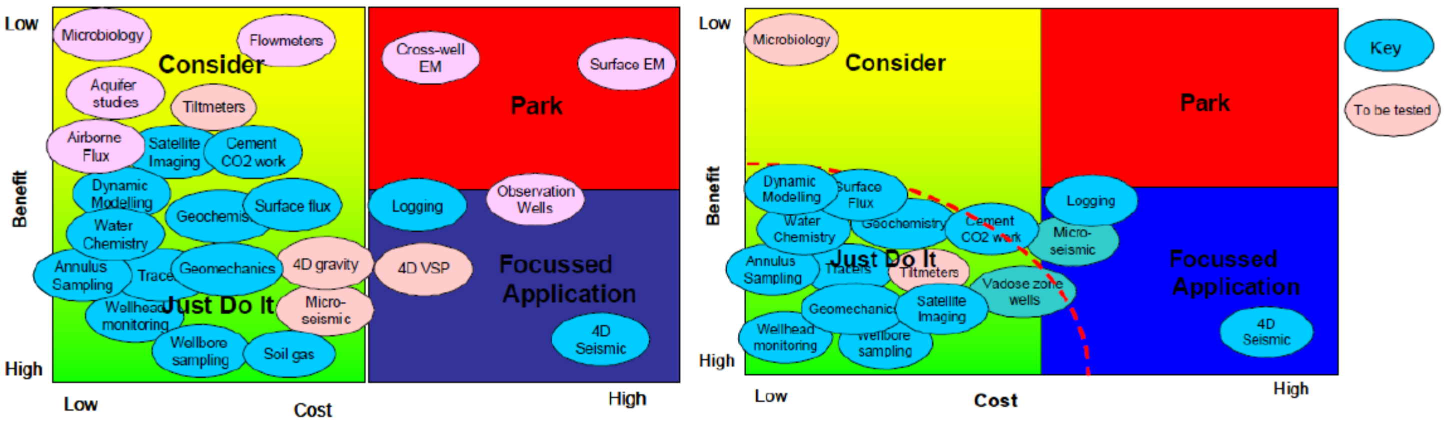

Fig 2. Boston Square approach applied for initial evaluation of monitoring technologies at In Salah (left panel) and final deployed technologies (right panel), Wright et al., 2010 *(IEA/CON/19/255, pg 32)*

TRL Assessment

The conventional technology readiness levels (TRLs) were adapted slightly for this study, as follows overleaf in figure 3. This figure shows an adapted table from the report, noting the TRL ratings as defined and described in the study, and comparisons with US-DOE and European TRL ratings.

TRL Level	1	2	3	4	5	6
Definition	Basic Technology Research	Research to Prove Feasibility	Technology Development	Technology Prototyping	Technology Demonstration	Technology Commercialis-ation
Basic Description	Basic principles formulated	Application of principles and characteristic proof of concept of technology	Laboratory-scale validation on relevant environments to identify preliminary product	Pilot-scale validation in relevant environments to optimise and demonstrate product operation and efficacy	Large-scale / full-scale demonstration in relevant environments	Operational under full range of expected conditions
US-DOE TRL Mapping	1	2,3	4,5	5,6	7,8	8, 9
European TRL Mapping	1,2	3	4	5,6	7,8	9

Fig 3. CCS technology readiness level definitions, descriptions and comparisons with other TRL rating systems *(adapted from IEA/CON/19/255, table 3-1, pg 38)*

Many CO_2 storage monitoring technologies that were adopted from the oil and gas or environmental industries are at TRLs of 4 to 5 and now only require validation and demonstration in CCS environments and readily available technologies are generally all in the 4 to 8 range. Most technologies however do still require additional feasibility studies to ensure they will be effective in site-specific conditions. More information can be found on page 40 of the study, where each of the 43 technologies looked at in this work are given a TRL rating.

Case studies

Several large-scale CCS projects were looked at to illustrate the application of monitoring technologies for CO_2 storage and their cost-benefit progress, ranging different geologic settings, regulatory policies and societal considerations, and interviews were completed with key personnel from the projects for this detailed insight into the monitoring programmes for particular storage programmes. The case studies selected include the Quest project (Alberta, Canada), Sleipner (North Sea, Norway), MRCSP Niagaran Reefs (Michigan, USA), In Salah (Algeria), Mountaineer (West Virginia, USA) and other pilot and smaller scale projects.

The key findings from these case study interviews are:

- The costs in monitoring can range from $10,000s (for routine operational pressure / temperature monitoring) to $1,000,000s (for 4D seismic methods)
- Economies of scale are evident in monitoring programmes; as greater volumes of CO_2 are injected, the costs per tonne decrease as programmes streamline
- There may be the opportunity to reduce monitoring based on technical thresholds rather than routine set intervals
- It is difficult to separate capital costs of construction, well drilling, site characterisation, administrative and technical support

- Pilot-scale projects that are focussed on research had high costs to validate technology but as programmes move toward more routine operations costs can be reduced
- Some early projects were not subject to as extensive regulations and so had simpler monitoring plans, therefore costing less
- Monitoring costs are a small fraction of the entire CCS project.

There are few examples of CO_2 storage projects that have completed a full lifecycle all the way into site closure; many projects are in the planning, baseline or operations phase. The In Salah and Mountaineer projects are two that have completed the full baseline to site closure process, which can provide some information to assess the cost of monitoring technologies throughout the entirety of a CO_2 storage project.

Along with the full lifecycle projects, natural analogues such as natural CO_2 fields, gas storage and offshore oil and gas can provide examples of long-term closure monitoring potentially applicable to storage projects. The following table (figure 4) summarises and provides a general cost estimation of the monitoring methods used in natural analogues that could be useful when considering the storage of CO_2 in CCS projects. Monitoring technologies provide options to address site-specific risks and accountability, and assessment of a storage site accounts for containment of the CO_2, monitoring / regulation of injection, plume activity and how to demonstrate safe and effective storage. The site-specific MRV plan will address risk assessment in capacity, containment, injectivity, contingency, mitigation and public acceptance using a range of monitoring and modelling technologies.

Analog	Risk	Monitoring	Costs
Natural CO_2 fields	CO_2 migration, leakage	Thermistors, pressure transducers	Low
	Releases along faults, volcanos	Monitoring of seismic activity, gas flux measurements along surface fault zones	Low
Offshore oil & gas	Casing pressure, leaks	Flow testing, BHP, temperature surveys, fluid levels, seabed surveys, airborne	Medium
	Legacy wells, 'idle iron'	Field inspections, water quality monitoring, benthic studies, seabed surveys, aerial reconnaissance	Medium
Natural gas storage	Well integrity	Well surveys, casing pressure surveys, cement bond logging	Medium
	Gas migration	Field pressure surveys, ambient air monitoring, airborne methane studies, gas sampling and composition analysis in other oil and gas wells, stored gas inventories	Low

Fig 4. Summary of Monitoring Performed in CO_2 Storage Analogues *(adapted from IEA/CON/19/255, table 4-3, pg 54)*

Cost Benefit Analysis

Optimised monitoring programmes are designed and adapted to address specific issues and potential risks in pre-injection, operations, post-injection and closure. This study provides considerations for monitoring and modelling technologies to address the six key risk categories; capacity, containment, injectivity, contingency, mitigation and public acceptance, with regards to costs and benefits to improve quantitative project-specific evaluation for monitoring programme design. The table below (figure 5) illustrates the evaluation components of the cost-benefit analysis. Higher ranks imply qualitative improvements. Individual technologies can be applicable to manage multiple risk categories and the metrics shown below are a simple measure of the number of risk categories that the given technology could address. In this study risk categories are classified as: capacity; containment; injectivity; contingency; mitigation; and public acceptance.

Cost Benefit Evaluation Metric	**Metric Values**					
	1	**2**	**3**	**4**	**5**	**6**
	Low Cost Benefit --> High Cost Benefit					
Risk Category	1	2	3	4	5	6
TRL	1	2	3	4	5	6
Accuracy / Resolution	undefined/ experimental	low	med-low	medium	med-high	high
Coverage	undefined	cm	meters	10s meters	100s meters	Kms
Reliability (inverse of operational limitations)	developmental	low	med-low	medium	med-high	high
Unit costs ($ /m^2)	**developmental**	**$100,000s**	**$10,000s**	**$1000s**	**$100s**	**$10s**

Fig 5. Summary of Input for Cost-Benefit Considerations *(adapted from IEA/CON/19/255, table 5-1, pg 62)*

Monitoring for managing capacity: operational monitoring and distributed acoustic sensing technologies seem to provide the highest cost-benefit to reduce the risk of capacity determination. The reliability of operational monitoring is much higher to reduce risk of capacity, but the distributed acoustic technology is able to be deployed so that it has a higher coverage, thus more beneficial.

Monitoring for managing containment: downhole pressure/temperature and annulus pressure testing methods provide the highest cost-benefit to reduce the risk of containment and downhole PT gauges within observation wells in the above-zone monitoring interval would provide early indication of loss of containment. Casing pressure monitoring, groundwater monitoring and tiltmeters also provide a higher cost-benefit rating. The reliability of downhole PT has proven to be higher than annulus pressure testing and geophysical methods see decreased cost-benefit due to the challenges of their dependency on the geological setting.

Monitoring for managing injectivity: this is important as reduced injectivity implies an increase in the cost per tonne of CO_2 storage, with costs rising due to well workover, remediation and the associated MMV activities. Downhole PT sensing provides a higher cost-benefit ratio to reduce the risk of injectivity; although reliability, coverage and accuracy is comparable with operation monitoring technologies, the cost of deploying downhole PT is less.

Monitoring for managing contingency: the role of monitoring for contingency is to validate the performance of a technology and verify the effectiveness of measures for unlikely events or storage performance. Downhole PT and annulus pressure testing were determined to provide the highest cost-benefit in this risk category (similar to the containment category). Other technologies like groundwater monitoring and tiltmeters also prove high in terms of cost-benefit.

Monitoring for managing mitigation: the risk for mitigation is in the unlikely event of loss of containment, capacity or injectivity, with technologies in place to decrease the likelihood or severity of such a risk event. Downhole pressure/temperature sensing, distributed temperature sensing and 3D surface seismic technologies prove highest in terms of cost-benefit to reduce the risk of ensuring mitigation. Unit cost, accuracy, resolution and reliability is highest in downhole PT, with 3D seismic providing the highest coverage and therefore highly effective.

Monitoring for managing public acceptance: monitoring technologies are used to address site-specific concerns of the local community. Groundwater monitoring and GPS technologies show the highest cost-benefit, followed by satellite interferometry (InSAR) in this risk category. InSAR does have higher unit costs than groundwater monitoring and GPS, with groundwater technologies the most mature method with the highest TRL.

Typically, monitoring programmes do not account for a significant proportion of total site operating costs, with research-based projects usually spending more on MMV compared to commercial-scale projects that tend to implement the minimum requirements necessary. Most CO_2 storage operations will be dictated by regulatory requirements in the location and require negotiation of monitoring plans with regulatory agencies. To improve cost-benefit, operators would benefit from including some degree of flexibility in their monitoring programmes such as tiered monitoring plans, quantitative thresholds and material impact criteria.

Different stakeholders will consider benefits differently, meaning these can be challenging to objectively quantify. This study identified the potential stakeholders and the key risks, benefits and 'red flags' and shows that may stakeholders involved may be concerned with deployment, technical performance and cost. Landowners, employees, regulators and the local community would likely be concerned with leakage, environmental impacts and safety, where researchers and government would be more concerned with wide-ranging risks (with higher costs) like injectivity, storage capacity, plume migration, subsurface effects and leakage. The stakeholder cost-benefit risk reduction analysis results are shown in Figure 6, below.

Stakeholder / Perspective	**Key Risks**	**Red Flags**	**Monitoring Options**	**Monitoring Costs**	**Key Benefits**
Executive, Industrial CO_2 Source	Costs, liability, safety, schedule, publicity	Safety incidents, leakage, cost overruns	System monitoring, wellbore integrity, high visibility surface monitoring	\$10,000s-\$100,000s	Ensuring system performance, regulatory compliance, environmental stewardship, controlling costs, verification of storage security, public assurance, worker safety, system reliability, accounting for incentives
C-Storage Project Manager	Costs, schedule, installation, performance, regulations, maintenance, design, etc.	Safety incidents, leakage, cost overruns, project performance			
Financial Backer/Insurer	Costs, liability, publicity, long-term security, regulations, leakage	Safety incidents, leakage, cost overruns, project performance			
Technical Consultant	Technology deployment, meeting regulations, satisfying client, costs	Technology failure, client dissatisfaction			
Monitoring Tech. Vendor	Technology performance, costs, technical challenges, installation & deployment, client satisfaction	Technology failure, client dissatisfaction			
Landowner	Leakage, reduction of property value, impact of field work, pipelines, wells, wellbore integrity, traffic, safety	Well leakage, ecosystem effects, wellbore integrity, accidents	Surface, near surface, safety, and wellbore integrity monitoring	\$10,000s-\$100,000s	Protecting environment, safety, reducing carbon emissions, economic benefit to local community, jobs, CO_2-EOR revenue from royalties
Local Community & Residents	Protection of near surface resources, leakage, catastrophic failure, environmental impact, traffic	Safety incidents, any leakage, exclusion from siting process, unexpected field work			
Non-Governmental Org.	Natural resources, environment, population, long-term climate change	Leakage, safety incidents, project performance, environmental impact			
Regulator	Meeting regulations, timely submittal, documentation, regulated limits, protection of near surface resources	Violations of regulations, safety incidents, leakage, environmental impact	Near surface, reservoir, wellbore system monitoring	\$10,000s-\$100,000s	Meeting regulations, worker safety, protecting environment, revenue from royalties/mineral rights, jobs, technology progress
O&G operator	Wellbore integrity, CO_2 migration into reservoirs, competition for EOR, mineral rights, pore space ownership	CO_2 interference with existing oil and gas operations and/or regulations, leakage			
Academic Research Community	Subsurface physical processes, research grants, accuracy, technology effectiveness	Technical errors, failure of technology, project performance, uncertain results	Reservoir monitoring	\$100,000s-\$1,000,000s	Knowledge sharing, advancing science, reducing GHG emissions, protecting human health and environment
Local Government	Local population opinion	Bad publicity, public resistance, safety incidents, leakage, project performance, environmental impact	Capacity, containment, safety	\$1,000,000s-\$10,000,000s	Reducing regional GHG emissions, protecting human health and environment, safety
National Government	National policy, economic development, protection of human health and environment				

Fig 6. Summary of Cost-Benefits & Risk Reduction for Stakeholders
(adapted from IEA/CON/19/255, table 5-3, pg 77)

Conclusions

The report concluded that there are opportunities to reduce the costs in the geologic storage of CO_2, particularly in monitoring operations, which will allow for the safe development of commercial projects. Such projects may find value in carrying out cost-benefit analyses when preparing their monitoring plans.

There has been progress in the monitoring of CO_2 storage, with the literature review suggesting that thousands of articles are available on the monitoring and modelling of CCS. Since the 1990's, CCS projects have progressed from research scale to more industrial scale operations in 2010-19. Such initiatives have helped improve confidence in storage monitoring applications. The integration of modelling and monitoring for storage provides an opportunity to confirm monitoring predictions with actual data, providing confidence in understanding processes in the subsurface. The report noted that although there are several cost-benefit studies giving examples how such an analysis can be integrated into CCS operations, there is no well-established methodology for cost-benefit analysis.

Much of the technology in CO_2 storage can only be proven in the field, meaning the TRL rating scheme used is slightly different than in other applications. The TRL of monitoring technologies seems suitable for supporting large-scale storage projects; more established methods such as operational monitoring and downhole pressure/temperature monitoring show higher ratings and many of the technologies have higher TRLs as they come from already-established oil and gas experience. Challenges do remain for storage monitoring, however, and there is room to refine and improve technologies for this.

In terms of monitoring costs, the report identified the large range in such costs for large-scale storage programmes; from \$10,000s for routine P/T measuring to \$1,000,000s for 4D seismic monitoring, meaning it was difficult to interpret the cost-benefit ratio here. It was also difficult to separate the costs of areas such as construction, well drilling, characterisation and site support. However, it was clear that economies of scale are evident, so as the volume of CO_2 injected increases, costs per tonne decrease.

Pilot-scale projects that were more focussed on research had high costs to validate technologies but as the project moves forward onto more routine operations costs become lower. Some early projects were not subject to such extensive regulations as newer projects and so had simpler monitoring undertakings, with lower costs incurred. It should be noted that storage monitoring costs are a small part of a CCS project and many monitoring methods have reasonable costs compared to other components of a CCS chain, such as drilling, pipeline and compression facilities.

Only a few projects have completed full baseline, operational and post-closure monitoring programmes. Other analogues for CO_2 storage can be used for examples in long-term monitoring activities.

Pressure-based monitoring provides a high benefit to cost ratio with the important potential to reduce multiple risk categories, whilst being relatively simple in terms of implementation and processing. The interviews carried out with project personnel show that CCS project managers consider subsurface P/T monitoring as one of the most valuable methods, along with groundwater monitoring and other near-surface and atmospheric methods which help reduce various risks, particularly in public acceptance. However, these latter technologies require establishment of stable pre-injection baselines and get scaled back during operations. This means that the reservoir zone and above-zone monitoring technologies ensure the risks in containment and leakage are well-managed, whilst using observational techniques (atmospheric and near-surface) to address stakeholder concerns.

Monitoring and modelling data is of the utmost importance to ensure safe and secure geological storage of CO_2 over time in any CCS project. There are some technologies that perform better in terms of certain project risks, so the consideration of technologies based on risks will complement both site selection and site operations to help ensure dependable economics in commercial projects. The cost-benefit analysis in this study is intended for use as a guideline for the selection of an optimal selection of monitoring technologies, from research and experience from other storage projects, to help to address site-specific goals. Such a systematic risk management plan would help to tailor MMV programmes to help select the best monitoring technologies for each particular project.

Costs of monitoring are easily quantified but the benefit can be difficult to measure. It appears that industrial-scale, commercial CCS projects (injecting around 1 Mt CO_2/year) have converged on costs around $1-4 million per year for their monitoring. Capital expenses like construction, characterisation, technical and administrative costs are hard to analyse in cost-benefit scenarios.

Obviously some monitoring technologies perform better than others to address project risks. The cost-benefit and summary exercise carried out for this study may be used as a guideline for developing more optimal monitoring programmes, remembering that a degree of flexibility in such planning would be beneficial.

The report recognises that there are no projects at the 50-100 Mt scale to provide examples of how monitoring works over areas of several hundred square kilometres. There is still a challenge with the accurate detection of CO_2 distribution in the subsurface due to relatively high costs and limited benefits, and also with imaging subsurface (injected) CO_2.

Other knowledge gaps documented include thresholds to help control monitoring costs and methods to help process the large amount of data that technologies output. A standardised methodology for cost-benefit analysis would be useful integrated into site characterisation, risk analysis, modelling and monitoring planning and system design. There is a lack of threshold / forward modelling approaches to design monitoring programmes that consider the material impact of CO_2 migration in relation to the monitoring technology and criteria for demonstrating plume stability. There is a need for a greater understanding of stakeholder acceptance risks for CO_2 storage in relation to performing high visibility near-surface and atmospheric monitoring.

Expert Review

The general consensus of the five expert reviews received were that this study is a valuable undertaking with important results for future commercial CCUS projects and a starting point to help understand the cost-benefit analysis for a projects' lifecycle in terms of their MMV plans. All recognised that there was a degree of difficulty with this work; the value of monitoring is not easy to quantify and many of the figures proposed are subjective. With regards to this, the report should not necessarily be used as a tool with absolute results, but as the report states, more of a guideline to use when selecting the suite of monitoring technologies suitable for a particular CO_2 storage project. The majority of the reviewers commented on how important the input from industry was; the experience and knowledge from actual operators is of particular use.

As a result of the comprehensive expert review process, the modelling section was recognised as being slightly less pertinent, so there report title and content were edited slightly to refocus more on monitoring. The technology readiness levels were altered slightly to match levels in other TRL approaches. More disclaimers were added to subjective areas such as monitoring fields and ratings and hidden costs were acknowledged more within the text after reviewers felt that items such as drilling, technical support, safety etc. were not considered enough.

Recommendations

To help improve the cost-benefit ratio of the monitoring and modelling to address risk in CO_2 storage projects, the following recommendations are suggested:

- To establish specific thresholds to control costs of monitoring
- To continue developing methods for the large amounts of data outputted with monitoring technologies
- Apply systematic methods for processing, risk assessment integration and interpretation of data, and control costs of ongoing data processing and interpretation
- Consider a systematic or standardised methodology for cost-benefit analysis that could be integrated into site characterisation, risk analysis, modelling, monitoring programme development and system design
- Develop options for confirming predictions in monitoring and modelling over exhaustive delineation of the CO_2 in the subsurface
- Implement threshold and forward modelling approaches to design monitoring programmes
- Evaluate criteria for demonstrating plume stability
- Apply systematic and process driven approaches to monitoring programmes with tiered cost-benefit analysis
- Develop monitoring strategies for sites with a lot of legacy wells and wellbore integrity issues
- Emphasise the understanding of stakeholder acceptance risks for project managers when employing high visibility monitoring methods, such as near-surface and atmospheric techniques.

There is a confidence in the array of monitoring technologies that are available for operations in the storage of CO_2, and the implementation of safe projects seems stable in the future. It is likely that more standardised monitoring programmes are likely to be deployed in regions with projects that have similar geologic settings, particularly as more industrial scale projects become operational. There is, however, opportunity for refinement and improvement of monitoring technologies. The cost-benefit ratio of reducing risk could be improved by more work into areas where modelling and monitoring have additional potential, such as offshore monitoring, automated data processing and options to confirm plume extents.

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Much of this study was based on pilot-scale field research completed on CO_2 storage monitoring and modelling over the past 20 years. Therefore, the authors would like to acknowledge all the scientists who dealt with many field challenges, budget issues, and stakeholder challenges to validate CO_2 storage technologies. Current CCS projects are benefiting greatly from these early efforts. The authors would like to acknowledge the guidance and support of IEAGHG project managers James Craig, Tim Dixon, Sam Neades, and Lydia Rycroft. The authors would also like to acknowledge input from Sallie Greenberg (Illinois Geological Survey), Mark Kelley (Battelle), Sue Hovorka (Texas Bureau of Geology), John Massey-Norton (AEP), Simon O'Brien (Shell), Phillip Ringrose (Equinor), Daiji Tanase (Japan CCS), and Steve Whittaker (Illinois Geological Survey). Their practical feedback on deployment of CO_2 storage monitoring technologies, cost information, and path forward for CO_2 storage projects was instrumental to the study. The study also benefited from the long-term support of CCS research by IEAGHG and governments around the world.

Monitoring and modelling of CO_2 Storage: The Potential for Improving the Cost-Benefit Ratio of Reducing Risk (IEA/CON/19/255)

Key Messages/ Executive Summary

This report describes how a cost-benefit analysis of geologic CO_2 storage monitoring and modelling technologies may effectively address project risks at manageable costs. Numerous monitoring and modelling options are available to provide assurance on CO_2 storage risks related to reservoir, above-zone, and surface during operations and the post-injection phase. There has been a great deal of research on CO_2 storage monitoring, modelling, and risk analysis, and it is challenging to comprehensively summarize these items in a useful format. The analysis was based on the collection of practical data and experience from CO_2 storage projects. Specific metrics were used to evaluate monitoring methods to provide a quantitative measure of cost-benefit. The results demonstrate that that there are opportunities to reduce costs in CO_2 storage monitoring operations, allowing for safe development of commercial CO_2 storage projects that provide meaningful reductions in CO_2 emissions. However, projects may benefit from including systematic cost-benefit analysis in monitoring plans, including flexibility in monitoring programs, and streamlining the operational monitoring schedules. Key messages of the study include the following items.

- There is a large range in monitoring costs: from $10,000s USD for routine operational pressure and temperature monitoring to $1,000,000s USD for 4D seismic monitoring. Many technologies have significant "hidden costs" like well drilling, technical support, safety, and administrative support. Thus, it is difficult to interpret the cost-benefit ratio for these methods.
- Commercial, industrial-scale CO_2 storage projects on the order of 1 Mt CO_2/year appear to have converged on monitoring costs of $1-4 million USD per year, depending on geologic setting, CO_2-EOR integration, and local regulations.
- Economies of scale are evident for monitoring programs. As projects inject greater volumes of CO_2 and streamline monitoring programs, costs on a tonne basis decrease.
- Monitoring costs related to system construction, well drilling, site characterization, administrative support, and technical support may be consistently accounted for in projects.
- Research-oriented pilot-scale projects had fairly high costs to validate technology, but there is a clear opportunity to reduce monitoring costs as projects move to routine injection operations.
- Monitoring costs are a small fraction of the entire CCS project, especially when compared to capital and operating costs for CO_2 capture and compression.
- Many of the monitoring methods have reasonable costs compared to the costs of drilling and constructing deep wells, pipelines, and compression facilities. The CO_2 storage monitoring costs are a small fraction (<5%) of most CCS projects overall budgets, especially in comparison to capital and operating costs for carbon capture.
- Some of the early projects were not subject to extensive regulations and had simpler monitoring programs with lower costs.
- Only a few projects have completed the full baseline, operational, and post-injection site closure monitoring. These projects provide examples of opportunities to streamline monitoring operations and costs, especially in the post-injection site closure period. Analogs for CO_2 storage also provide monitoring examples for very long-term CO_2 monitoring efforts.

Overall, there is confidence in the array of monitoring technologies available for CO_2 storage projects, and the path forward for implementing safe CO_2 storage projects appears stable. Current operational CO_2 storage projects have been able to streamline their monitoring programs, focus on the most useful monitoring methods that address project specific risks, and control costs. This trend is likely to continue as more industrial scale projects become operational. More standardized monitoring programs are likely to be deployed in regions with many projects that have similar geologic settings.

Recommendations

CO_2 storage technologies continue to develop and mature as more CCS projects are implemented. CO_2 storage monitoring of wellbore integrity and geomechanical effects have had the largest effect on projects to date. There are no projects at the 50-100 Mt scale to provide examples of monitoring several hundred square kilometer areas. Accurate detection of CO_2 distribution in subsurface remains a challenge with high costs and limited benefit at times. Recommendations for improving the cost-benefit ratio of CO_2 storage monitoring and modelling to address risk are provided as follows:

- Establish specific thresholds to help control monitoring costs, especially for delineating the CO_2 plumes and pressure fronts in terms of CO_2 saturation levels and pressure changes.
- Continue to develop methods for processing the large amount of data that newer monitoring technologies output more for commercial CO_2 storage operations.
- Apply systematic methods for processing, risk assessment integration/updates, and interpretation data from some geophysical monitoring technologies provide clear results and control costs of ongoing processing and interpretation.
- Consider a systematic or standardized methodology for cost-benefit analysis that may be integrated into site characterization, risk analysis, modelling, monitoring program development, and system design.
- Develop options for confirming the monitoring/modelling predictions rather than exhaustive delineation of the CO_2 in the subsurface.
- Implement threshold and forward modelling approaches to design monitoring programs that consider the material impact of CO_2 migration in relation to the monitoring technology.
- Evaluate criteria for demonstrating plume stability where geologic conditions may result in long-term CO_2 migration within a reservoir but no consequential leakage.
- Apply systematic and process driven approaches to CO_2 monitoring programs with tiered cost-benefit analysis to aid in managing project risk, costs, regulatory requirements, and field operations.
- Develop monitoring strategies for sites with many legacy oil and gas wells and wellbore integrity issues.
- Emphasize understanding of stakeholder acceptance risks for CO_2 storage project managers in relation to performing high visibility near-surface and atmospheric monitoring.

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1.0 Introduction

This report presents a cost-benefit analysis of geologic CO_2 storage monitoring and modelling technologies. The focus of the study was to evaluate how monitoring and modelling may effectively address project risks at manageable costs. The analysis emphasized collecting factual data and experience from CO_2 storage projects. Specific metrics were defined for the monitoring methods to provide a quantitative measure of cost-benefit. The results portray the status of current CO_2 storage applications and opportunities to reduce costs, allowing for safe development of commercial CO_2 storage projects that provide meaningful reductions in CO_2 emissions.

1.1 Background

Research on geologic CO_2 storage has progressed from conceptual studies and pilot-scale demonstrations in the 1990s to large-scale carbon capture and storage (CCS) projects at scales of 1 million metric tonnes per year (Mt/year). This research has produced a large amount of information on monitoring and modelling CO_2 storage. Currently, projects like Sleipner, Quest, Aquistore-Boundary Dam, Snøhvit, and industrial-scale U.S. DOE (Department of Energy) demonstrations have moved into more regular CCS operations. Many of these sites have streamlined their operations to include the most effective technologies that address site specific risks for their CO_2 storage system. These projects provide an understanding of how monitoring options were selected, tangible monitoring costs, and direct evidence of how monitoring programs have evolved over the CO_2 storage life cycle.

End users intended for the report include CCS operators, technology vendors, regulators, financial backers, technical consultants, oil & gas operators, and the research community. In general, these stakeholders may be involved in establishing monitoring programs for commercial-scale CO_2 storage applications. Where possible, results were summarised in easy to use tables, graphics, and summaries to provide functional products for end users with different levels of experience with CCS.

1.2 Objectives

The objective of this study was to evaluate the monitoring and modelling of technologies associated with large-scale storage of CO_2 in geological formations to describe how these technologies have addressed project risks related to factors such as capacity, containment, injectivity, contingency, risk mitigation, and public acceptance. A cost-benefit review of each technology was completed in context of case study applications:

1. Commercial scale CCS projects were selected (establishing the projects with available storage technology information).
2. The technologies to be included in the review were compiled and the information sources were determined to find where much of the information was going to be available.
3. Technology reviews were conducted using a combination of in-house expertise and interviews with key persons associated with large-scale projects.
4. The technologies were categorised based on their cost-benefits in how they are beneficial to the principle risk categories defined above.

The study was designed to determine the most effective monitoring technologies in terms of specific metrics including life-cycle costs, data processing, accuracy, limitations, baseline monitoring requirements, geologic settings, frequency, and areal coverage. The analysis evaluated the impact of each technology and priorities for future developments based on technology readiness supported by large-scale CCS case studies, including both onshore and offshore CCS applications throughout the world. This approach integrates reviews of monitoring methods, technology readiness, large-scale CCS case studies, and cost benefit analysis.

As CCS advances to more widespread commercial applications, the cost-benefit analysis provides timely guidance to support the development of new projects. Results from the cost-benefit analysis address some key questions like the following:

- What stage of development are various monitoring CO_2 storage technologies at and what further developments are required to reach commercial scale deployment?
- Are there any emerging technologies (measurement, modelling, sensing, etc.) with favourable cost-benefit impacts?
- What improvements in monitoring and modelling technology are still required to improve predictions in injectivity, containment, capacity and address contingency, risk mitigation and public acceptance?

A primary objective of the study was to assess several industrial-scale CO_2 storage case studies to provide real-world evidence on the advantages, costs, and limitations of various monitoring technologies.

1.3 Scope

The study included components to select commercial scale CCS projects, define monitoring technologies, and categorise the technologies based on key cost-benefit metrics. The research approach included the following main tasks:

- a literature review of CO_2 storage monitoring and modelling advancements over the last twenty years,
- a technology readiness level assessment of monitoring technologies,
- case studies of large-scale CCS projects (50-100 Mt) monitoring programs, and
- a cost benefit analysis of select research and development (R&D) technologies.

The analysis approach concentrated on applied research and development to define the potential for improving the cost-benefit ratio of reducing risk with monitoring and modelling technologies. This methodology leveraged experience with CCS projects throughout the world, including site screening for carbon storage, site characterization, reservoir modelling, operational monitoring, and post-injection site closure. Practical considerations were emphasized for a wide variety of monitoring technologies for both government and industrial clients, including dealing with cost limitations in respect to project requirements. The analysis was focused on providing perspective on monitoring and modelling methods given:

- early CCS research for pilot scale experiments and academic research,
- emergence of large-scale CCS projects with a longer period of CCS operations, and
- technologies employed in traditional oil and gas operations.

This approach integrated reviews of monitoring methods, technology readiness, large-scale CCS case studies, and cost benefit analysis. The study emphasized applied research and development to define the potential for improving the cost-benefit ratio of reducing risk.

The study benefited greatly from interviews with key personnel (Table 1-1) from several industrial-scale CCS projects. These interviews provided practical feedback on experience with a wide range of monitoring and modelling technologies. In addition, the various projects had site specific risk factors that featured in their considerations.

Table 1-1. List of key personnel from CCS projects interviewed for the current study.

Point of contact (Organisation)	Project(s)
Sallie Greenberg (Illinois Geological Survey)	ADM Decatur CCS Project
Mark Kelley (Battelle)	Midwest Regional Carbon Sequestration Partnership Niagaran Reef CO_2-EOR Project
Sue Hovorka (Texas Bureau of Geology)	Petra Nova CCS Project
John Massey-Norton (AEP)	Mountaineer CCS Product Validation Facility
Simon O'Brien (Shell)	Quest CCS Project
Daiji Tanase (Japan CCS)	Tomakomei CCS Project
Steve Whittaker (Illinois Geological Survey)	Weyburn, ADM Decatur, CSIRO CCS Projects

1.4 Assumptions/Limitations

The analysis was focused on currently used monitoring technologies for both onshore and offshore CO_2 storage projects. The cost-benefit analysis was performed relative to a broad range of CO_2 storage risk categories including capacity, containment, injectivity, contingency, risk mitigation, and public acceptance. The review was focused on more developed technologies i.e. with a Technology Readiness Level (TRL) of 6-9. Monitoring technologies included in the review were aligned with the IEAGHG monitoring selection tool. Efforts were made to include as many CO_2 monitoring technologies as possible, but emphasis was given to methods with applied history, data availability, and established costs.

Cost data was based on a combination of in-house project experience, interviews with personnel for select commercial scale projects, and publicly available reports. As much as possible, historical invoices were used as a cost basis. Since many of the monitoring technologies are available on an open market, costs may vary. In addition, site specific factors related to geology, subsurface conditions, surface access, and location will affect costs. Many technologies include "hidden costs" like well drilling, technical support, safety, and administrative support that were not explicitly tracked for projects. Thus, the costs in this report tend to reflect base vendor costs.

Interview feedback was summarised for the case studies and other areas of the report. It should be noted that much of the feedback provided in the case study interviews was very site specific based on the experience and risks present at each site. Therefore, these case studies should not be considered as an all-inclusive guidance. Rather, they are examples of the process-based approaches to implement CO_2 storage monitoring and modelling programs.

The study was intended to provide only a general guidance for CO_2 storage projects. A site-specific CO_2 storage project would require field work such as seismic surveys, drilling, geophysical logging, reservoir tests, detailed reservoir modelling, and system design. The results of this report should not be viewed or interpreted as a definitive assessment of suitability of monitoring or modelling technologies to allow CO_2 sequestration to be carried out in an economic manner.

2.0 Literature Review

A literature review was completed to provide a summary of the status of monitoring and modelling technologies based on the six risk categories, substantiated by examples of approaches in major large-scale CCS projects. Section 4 explains the risk categories considered for the study. The review highlights the status of monitoring technologies, general timeline of CCS industry progress, and integration of monitoring and modelling. The section details advancements by industry and learnings over the years for the choice of and improvements in various key technologies for CO_2 storage applications.

2.1 Broad Literature Review on CO_2 Storage Monitoring

Conventional bibliographic searches were completed to summarize technical articles on CO_2 storage monitoring, modelling, and risk assessment studies generated over the past couple of decades. Google Scholar, for example, presented over 693,000 CCS monitoring citations. These results demonstrate the somewhat overwhelming extent of information concerning monitoring technologies available to the public and new and existing CCS operators. Refined searches using Scopus, SciTech and Web of Science search engines were conducted for storage criteria and risk assessment using keyword logic refinement trees for atmospheric, surface/near-surface, and reservoir CCS monitoring (Figure 2-1). Results were tallied from each search engine and a list of monitoring technologies were created for each monitoring zone. A total of 1,242 articles were classified for atmospheric, 1,466 articles for surface/near-surface, and 3,293 articles for reservoir monitoring (Figure 2-2).

This literature summary suggests that majority (55%) of research on CO_2 storage has focused on the reservoir zone. The reservoir zone is the focus of oil & gas operators attempting to maximize recovery in oil & gas fields. Consequently, many of the technologies available to monitor or characterize subsurface conditions for CO_2 storage were adopted from the oil & gas industry. Similarly, many near surface and atmospheric monitoring methods were adopted from the environmental or remote sensing industry. Some challenges introduced for CO_2 storage included monitoring large areas in the subsurface or surface, tracking indirect indicators of CO_2 migration, and accounting for the multi-phase behavior of CO_2. The monitoring literature data was reviewed and refined to common technologies that address the following factors: capacity, containment, injectivity, contingency, mitigation, and public acceptance. Many monitoring methods address multiple factors and require periodic updating and integration into overall CO_2 storage project plans. The finalized list of technologies was divided into three main categories (atmospheric, surface/near-surface, and reservoir) and then further separated according to the risk assessment categories that each of the technologies addressed.

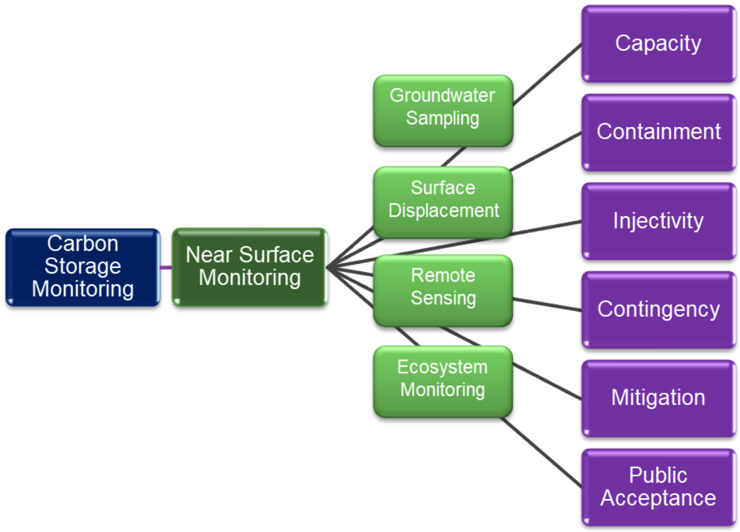


Figure 2-1. Example logic tree literature search criteria of Near Surface Monitoring articles.

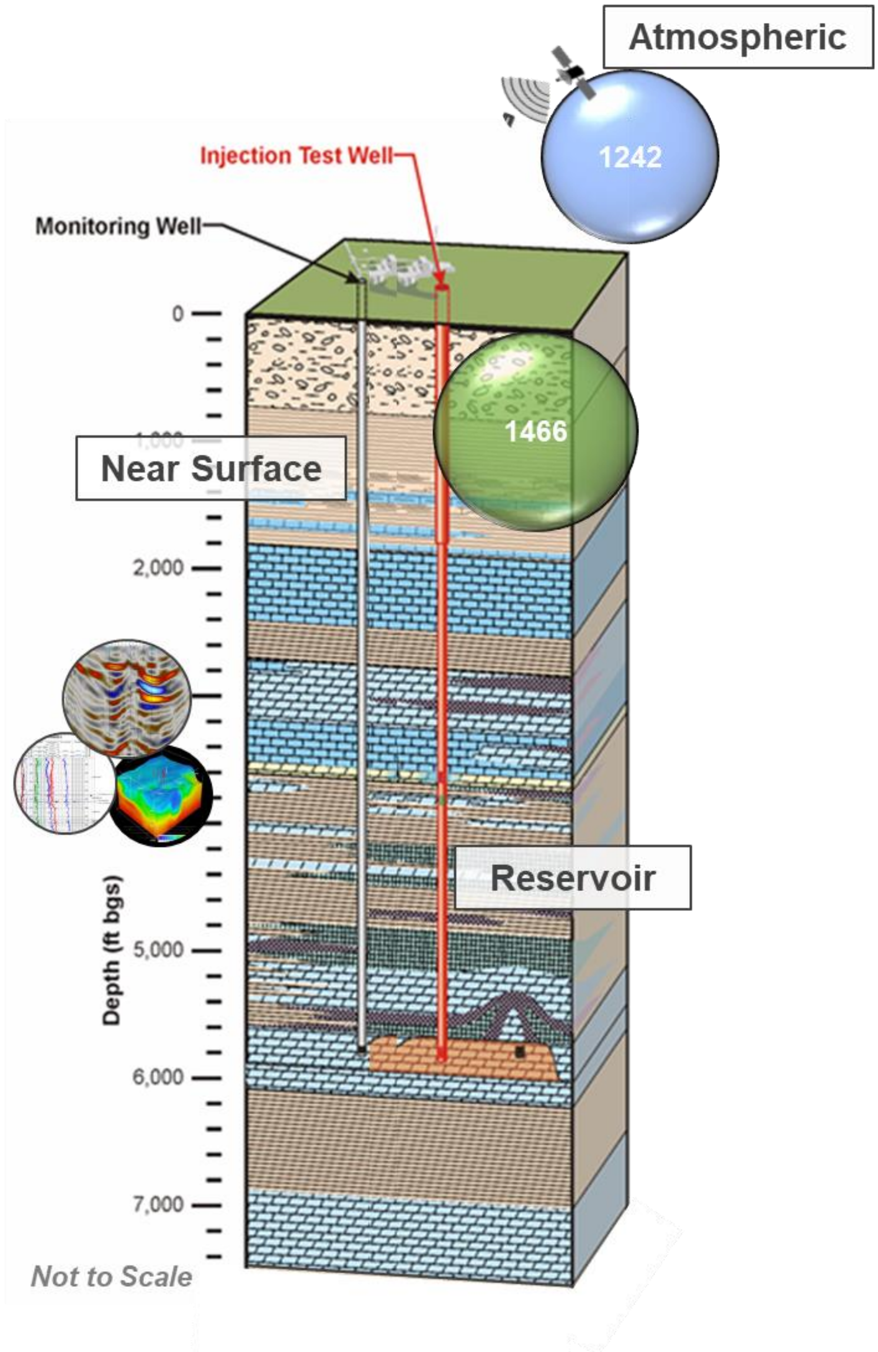


Figure 2-2. Carbon Capture and Storage monitoring article results from Scopus, SciTech, and Web of Science bibliographic searches. Search results determined Atmospheric (1,242), Surface/Near Surface (1,466), and Reservoir (3,293) articles. The search results illustrate the amount of research completed for the different categories.

2.2 Timeline of Major Events in CO_2 Storage Monitoring and CCS Projects

A timeline of major events in CO_2 monitoring technology was generated to illustrate trends in application of monitoring and CO_2 storage projects (Figure 2-3). CO_2 injection and associated storage projects date back to the 1972 Chevron SACROC CO_2-EOR flood. From the 1970s to 1990s, CO_2-EOR expanded in the Permian Basin and other parts of the U.S. In the 1990s, the CO_2 sequestration concept to offset GHG emissions was introduced with some key meetings like the JOULLE II meeting and the formation of IEA GHG R&D Programme. The Sleipner project also started CO_2 injection operations in the North Sea (Ringrose et al., 2013). In the early 2000s, numerous fundamental research and pilot scale programs were completed, including some key monitoring focused projects like the Frio Experiment (Doughty et al., 2008), Nagaoka CO_2 Storage Pilot (Mito and Xue, 2008), U.S. DOE Carbon Sequestration Partnerships (U.S. DOE, 2017), ZERT program (Strazisar et al., 2009), Gorgon Project baseline monitoring (Flett et al., 2009), and In Salah CCS project (Wright et al., 2010).

From 2010-2019, more industrial scale projects have been deployed like Quest, Snøhvit, Aquistore, ADM Decatur, Petra Nova, and the U.S. DOE CarbonSAFE program. A few projects have gone through a full life cycle of pre-injection monitoring to site closure like the Mountaineer Integrated CCS project and the In-Salah CCS project. To date, the Sleipner project is the largest CCS project with over 15 Mt injected to date. Notably, few projects have injected very large volumes of 50-100 Mt CO_2. As shown in Figure 2-3, CO_2 levels in the atmosphere continued to increase significantly during this time period, emphasizing the need for more meaningful CCS projects to reduce GHG emissions.

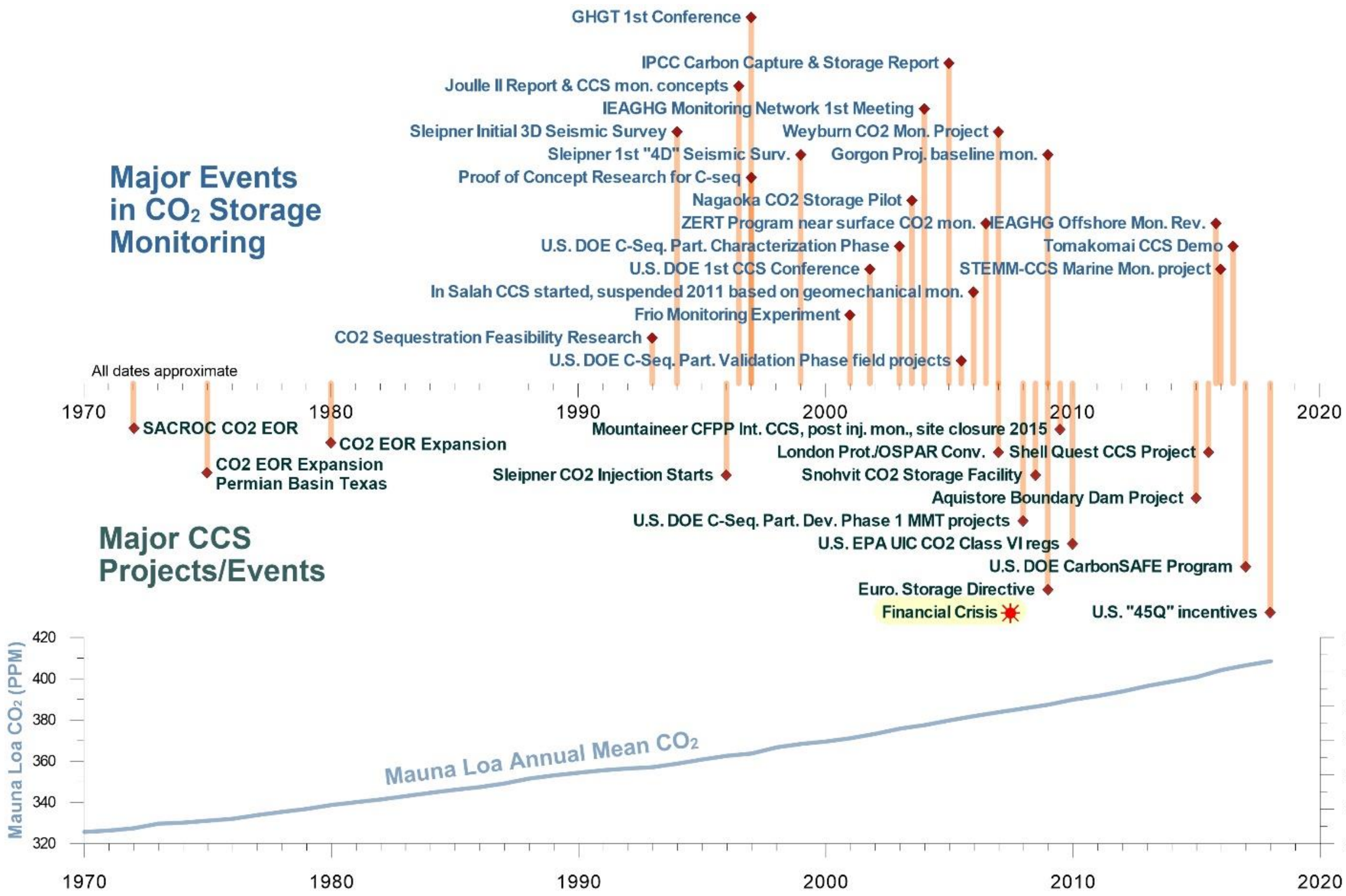


Figure 2-3. Timeline infographic of major CS monitoring events and projects illustrating the occurrence of major events in CO_2 storage monitoring and major CCS projects/events.

2.3 Key Monitoring Studies

As described above, there is a great deal of technical literature available on monitoring and modelling technologies for CO_2 storage applications. There are some key studies that provide background and examples of monitoring applications and cost benefit analysis for the benefit of industry decision makers, regulators, and stakeholders. Also, the field projects listed here all benefited from their monitoring programs to address natural and/or man-made issues.

The In Salah CO_2 Storage Project - The In Salah CO_2 storage project provides an example of an integrated, industrial-scale carbon capture and storage project. The project was completed from 2004-2011 in central Algeria, where 3.8 Mt CO_2 from a natural gas processing plant were injected into a 1900 m deep sandstone formation with three horizontal injection wells. A wide variety of monitoring technologies were employed at the In Salah project. A cost-benefit evaluation of the monitoring technologies was also developed by Ringrose et al. (2013) and Wright et al. (2010) where nearly all the monitoring methods evaluated were rated as low cost and high benefit (Figure 2-4). During injection, InSAR monitoring detected up to 20 mm of surface uplift, which was confirmed with modelling to be related to CO_2 injection. In addition, there was some indication from system monitoring of possible fracture flow into the caprock and some wellbore integrity issues. Thus, these items were identified in quantified risk assessments for the project. One important result of the In Salah project was that InSAR monitoring revealed the presence of geomechanical effects caused by CO_2 injection and some wellbore integrity issues, which contributed to the decision to stop the project among other factors (IEAGHG, 2015).

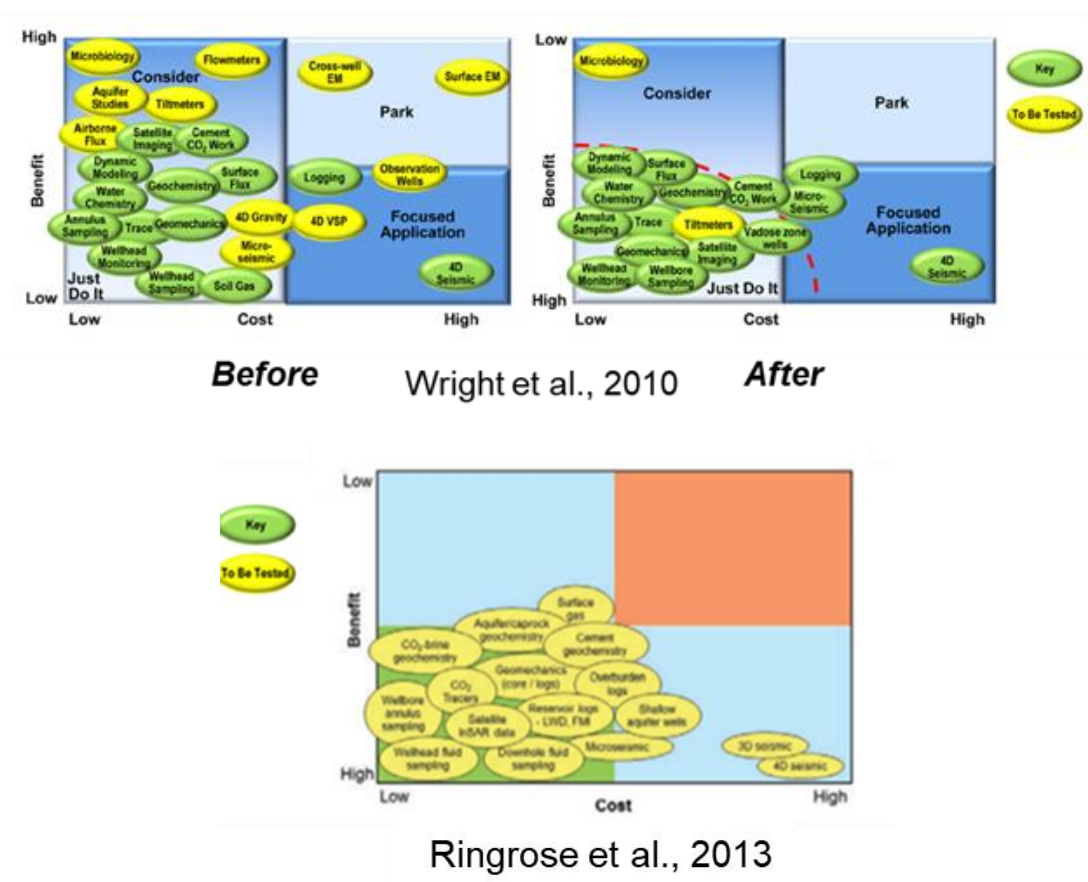


Figure 2-4. In Salah Cost benefit Boston Square Analysis (from Ringrose et al., 2013; Wright et al., 2010).

The project included baseline, operational, and post-injection monitoring from 2004-2011 (Mathieson et al., 2011). This monitoring data resulted in analysis and insights on the impacts of CO_2 storage in the deep subsurface and surface. Ringrose et al. (2013) summarised the key lessons learned from the demonstration project:

> "1. Monitoring should be part of the Field Development Plan (FDP) and routine field operations.
>
> 2. The suite of monitoring technologies to be deployed at any CO_2 storage site mainly comprises standard oilfield techniques and practices, with surface monitoring methods derived from standard geotechnical and environmental monitoring practices.
>
> 3. Satellite InSAR data has been especially valuable in understanding the geomechanical response to CO_2 injection, but needs to be integrated with high quality reservoir and overburden data and models.
>
> 4. The storage monitoring programme needs to be designed to address site-specific leakage risks identified in the selection phase, but also needs to be adapted during the operational phase.
>
> 5. Legacy wellbore integrity is a key leakage risk that has to be effectively managed.
>
> 6. Acquisition, modelling and integration of a full suite of baseline data, including the overburden, are vital for evaluating long term storage integrity.
>
> 7. CO_2 plume development is far from homogeneous and requires high resolution data for reservoir characterization and modelling.
>
> 8. Injection strategies, rates and pressures need to be linked to detailed geomechanical models of the reservoir and the overburden. Early acquisition of geomechanical data in the reservoir and overburden, including extended leak-off tests, is advisable.
>
> 9. Regular Risk Assessments should be conducted to inform the on-going operational and monitoring strategies."

It should be noted that the In Salah site had distinct geologic features, and geomechanical deformation is not a common issue for other CO_2 storage sites. The site was provided information on how monitoring may support effective management of project risks for CO_2 storage (Ringrose et al., 2013).

Weyburn CO_2 Monitoring & Storage Project - The Weyburn CO_2 Monitoring & Storage Project was established by the IEAGHG, Petroleum Technology Research Centre, and University of Regina in 1999 to monitor CO_2-EOR at the Weyburn Oil field in Saskatchewan, Canada (Wilson et al., 2004). Industry, research, and government organizations contributed to 81 separate tasks related to CO_2 storage. Central themes of the project were geological characterization, monitoring and verification, capacity/distribution predictions/economic limits, and long-term risk assessment. The project included demonstration of production monitoring of EOR operations, reservoir fluid chemistry, seismic reservoir properties, microseismic activity, and surface soil gas monitoring. Monitoring results were integrated into a long-term risk assessment modelling. The research determined that wellbore leakage presented the greatest risk factor to the CO_2 storage system, because there are more than 3,000 legacy wells in the field. Much of the monitoring was focused on seismic imaging of the CO_2, geochemistry, soil gas, and reservoir simulations. The monitoring program was reported as $9.1 million Canadian in 2004, or 56% of the total project budget (Wilson et al., 2004 [page 4]). In 2010, a landowner claimed elevated CO_2 levels in soil on their property related to CO_2-EOR. However, subsequent investigations by several parties did not detect any evidence of CO_2 leakage and observed elevated CO_2 was related to natural and expected soil processes, proving the benefit of baseline monitoring (Romanak et al., 2013).

Nagaoka CCS Pilot-Scale Test- The Nagaoka CCS Pilot-Scale Test was an experimental CO_2 injection project completed in 2000-2015 in Japan. A total of 10,400 tonnes (t) CO_2 were injected into the Haizume sandstone reservoir 1,100 m deep. A detailed monitoring program was completed at the site, including cross-well seismic, geophysical wireline logging, pressure/temperature monitoring, geochemical sampling, and modelling (Kikuta et al., 2005; Mito & Xue, 2008; Sato et al., 2010). The Nagaoka project provides an example of detailed monitoring at a site with challenges related to the geological setting, seismic activity, geomechanics. In fact, a natural earthquake occurred about 20 km from the site during the CO_2 injection period, so the monitoring program was important to address concerns about induced seismicity (Xue, 2010). Additional monitoring required to address the nearby earthquake included surface system inspections, cement bond logging, and borehole televiewer surveys to ensure the well system was not damaged. A fair amount of analysis was also required to verify the earthquake was not linked to the CO_2 injection as part of the monitoring, measurement, and verification (MMV) at the site. The project work is especially pertinent to areas like the central U.S., where induced seismicity has a high visibility in the U.S. media.

Frio Brine Pilot Experiment **-** The Frio Pilot experiment, funded by U.S. DOE, was one of the first dedicated CO_2 injection tests in the U.S. which injected 1,850 t of CO_2 into the Frio Formation in 2004-2006 (Sakurai et al., 2005; Hovorka et al., 2006). A wide variety of monitoring technologies were tested in the pilot, including geophysical logging, a 3-D seismic survey, geochemical sampling, introduced tracer samples with U-tube, time lapse cross well seismic, soil-gas tracers, tracers and shallow-aquifer groundwater monitoring. The pilot performed some of the first fundamental monitoring of CO_2 sequestration processes in a brine-only setting. The test illustrated some of the challenges with intensive monitoring, complex natural variations in near surface conditions, and rapid migration of CO_2 in high permeability reservoirs. As a proof-of-concept type test, the Frio Pilot was a successful demonstration that the CO_2 storage process could be monitored in the subsurface and surface. However, the test set a fairly ambitious precedent for subsequent CO_2 injection tests.

IEAGHG Monitoring Network **-** The IEAGHG has organised an ongoing international monitoring network to share experience and updates on CO_2 monitoring projects. The network has had a series of eleven meetings from 2004-2019. These reports document each meeting and include details of the application of different monitoring techniques and, in some cases, the challenges associated with tracking CO_2 in the subsurface. These network meetings also include summaries of monitoring activities at key pilot and demonstration CO_2 storage sites. In addition, the IEAGHG has generated many reports on CO_2 monitoring (IEAGHG 2005; 2006; 2007; 2008; 2009; 2010; 2011a; 2011b; 2013; 2015a; 2015b; 2015c; 2015d; 2017; 2019).

The IEAGHG monitoring network provides an international perspective and continuity to CO_2 storage monitoring technology evaluations. The original 2004 IEAGHG monitoring workshop listed three requirements for the safe and effective storage of CO_2 in geological formations:

1. Worker and public safety,
2. Local environmental impacts to groundwater and ecosystems,
3. Greenhouse Gas mitigation effectiveness.

Notably, the workshop also concluded that there was "such an extensive toolbox of monitoring techniques, new injection projects need guidance on what to measure and where." Also, some monitoring methods were "more appropriate in certain locations due to their suitability to particular climate and local environmental conditions." Since 2004, CO_2 monitoring options have expanded. End users have an even larger array of technologies to contemplate with emerging technologies like distributed sensing using fibre and microsensors. The emphasis on safety, local impacts, and greenhouse gas mitigation effectiveness may have been reduced in lieu of methods focused on imaging CO_2 distribution in the subsurface and geomechanics.

U.S. DOE-NETL Monitoring, Verification, and Accounting Best Practices Manual **-** U.S. DOE-NETL produced a Monitoring, Verification, and Accounting best practices manual in 2009 and updated the document in 2012 and 2017 (US DOE 2012; 2017). The document provides a technical guide for atmospheric, near-surface, and subsurface monitoring technologies. The manual rated CO_2 monitoring tools based on their maturity or field readiness in terms of early development stage, development stage, or commercial stage (Table 2-2). The document also listed monitoring technologies available for U.S. EPA permitting for CO_2 sequestration wells. Risk-based monitoring strategies workflows for developing site-specific monitoring plans are also presented in the best practices manual using a cost benefit approach. Example field tests of monitoring tools and techniques are also presented including useful examples of the monitoring plans, results, and lessons learned from field tests.

Table 2-2. CO_2 Monitoring Technologies Listed in the DOE MVA best practices Manual (2017).

Early Development Stage	Development Stage	Early Demonstration Stage	Commercial Stage
Passive tracer soil gas sampling	Atmospheric passive tracer sampling (flask, sorbent)	LIDAR/DIAL	CRDS, NDIR based CO_2 sensors
Ecosystem hyperspectral, multi-spectral imaging of vegetative stress	Multi-tube remote samplers, windvane samplers	Eddy Covariance flux towers	Flux accumulation towers
Remotely operated vehicle deployable-deep-ocean gravimeters, borehole gravity	Portable isotopic carbon analyzers, fiber optic sensors for soil-CO_2	Soil gas tracer sampling, soil-carbon analysis	Soil/Vadose flux accumulation chambers
Cross-well electrical resistivity tomography (ERT), surface-downhole ERT	Cable-less ruggedized sensors for downhole P.T. corrosion	Tiltmeters InSAR/PSInSAR, GPS	Shallow groundwater sampling, geochemical analysis
	Fiber-optic distributed temperature sensor (DTS) system, Distr. thermal perturbation sensor (DTPS)	Cross-well seismic, passive (micro) seismic	Wireline-based samplers
	Fiber-optic geophone tech. for borehole seismic surveys, cableless data acquisition for multicomponent, 3-D seismic	U-tube sampling, modified reservoir fluid sampling system, gas membrane sensor system	Density, neutron porosity logs, pulsed neutron tools (PNT), acoustic pulsed neutron tools (PNT), acoustic logging, dual-induction logging
	Controlled-source electromagnetic (CSEM) surveys	Continuous and autonomous monitoring of CO_2 storage by pressure monitoring	Downhole/wellhead pressure, temperature gauges, flow meters, sonic logging, oxygen-activation logs, radioactive tracer surveys, corrosion mon.
	Combining GPS, InSAR data with seismic and geochemical data Integrating seismic techniques with other geophysical tools		Time-lapse surface seismic (3-D, 2-D) Borehole seismic (vertical seismic profile [VSP])
			Remotely controlled downhole sensors and fluid control equipment

STEMM-CCS (2016-Present) **-** The Strategies for Environmental Monitoring of Marine Carbon Capture and Storage (STEMM-CCS) program is focused on sub-seabed carbon dioxide storage and offshore monitoring technologies. The STEMM program includes analysis of natural gas seeps, gas chimneys, and seawater chemistry as well as test releases, sensor development, modelling, and ecosystems monitoring. The North Sea Goldeneye site is a primary offshore controlled release test site for the program. Much of the STEMM work is aimed at detecting CO_2 migration and leakage at the seabed and near seabed. Since many future international CCS projects may be in areas with offshore carbon storage resources, the project provides useful information on monitoring options for developing areas. In addition, many of the monitoring technologies available for CCS may be somewhat limited to onshore locations, so the STEMM program is a useful resource for offshore operations.

2.4 Summary of CO_2 storage Monitoring Technologies

Monitoring technologies for CO_2 storage were summarised to illustrate the various options available for tracking CO_2 storage in the subsurface, CO_2 plume dimensions, CO_2 migration/leakage, surface operations, and safety of human health and the environment (Table 2-3). The monitoring technologies included in the review were aligned with the IEAGHG monitoring selection tool. The study was focused on existing monitoring technologies for both onshore and offshore CO_2 storage projects with TRL of 6-9. Emphasis was given to methods with applied history, ready availability, and established costs. Criteria for evaluating CO_2 storage monitoring technologies were selected to provide metrics on monitoring equipment, monitored zone, costs, advantages, and limitations. Fields included in the review included the following items:

Name - industry name for monitoring method/technology.

Description - general description of how the technology works and parameters measured.

Monitored Zone - listing of zones monitored (reservoir, near-surface, surface, wellbore).

Equipment - summary of equipment necessary to deploy technology.

Pre/Post Processing Requirements - listing if technology requires baseline & repeat surveys, processing of data, interpretation, indirect indicator of CO_2 or direct measurement.

Frequency - description of how often method collects data.

Domain - description if technology covers point or length (X), area (XY), or 3D (XYZ).

Accuracy/Resolution - description technology precision measurements for target parameters.

TRL/Field Application - general rating of technology maturity and availability for field deployment in terms of specialized research, mature, common.

Coverage - summary of area (cm^2-km^2) or length (cm-km) covered by technology.

Costs - general range of costs for technology deployment for industrial CO_2 storage application.

Unit Costs - costs divided by domain.

Risk Category - listing of risks addressed by technology (capacity, injectivity, containment risk mitigation, contingency, public acceptance).

Advantages - description of benefits provided by the technology for CO_2 storage monitoring.

Disadvantages - general description of limitations of technology.

These fields provide specific cost-benefit metrics for CO_2 storage monitoring technologies. The pre- and post-processing requirements can impact costs, especially if baseline and repeat monitoring events are required. In addition, processing and interpretation can increase costs and possibly lead to unclear results. The domain and coverage parameters were defined to portray what portion of the storage system the monitoring technology focuses on (i.e. the XZ reservoir zone, or the XY area at the surface) and how large a domain is typically addressed. Accuracy was considered a metric in terms of low-resolution methods versus more indirect methods that rely on some secondary indicator of CO_2 like surface uplift, or changes in electromagnetic signal. Coverage, domain, and unit costs depict the dimensions addressed by the technologies. General cost ranges were listed based on vendor quotes and other research. Low cost methods that cover large areas might be considered more beneficial than high cost methods focused on small areas. This metric was expressed as a "unit cost," which is the monitoring cost per event divided by the coverage. The risk categories, discussed in detail in Section 4, typically addressed by the monitoring methods to meet monitoring goals were classified into capacity, containment, injectivity, contingency, mitigation, and public acceptance. Finally, the advantages and disadvantages of deploying the technology in the field were listed in relation to industrial CO_2 storage projects.

The monitoring table is not intended to be a user guide for deploying the various monitoring technologies. In addition, many of the fields are somewhat subjective as site specific conditions can significantly impact the various fields used to describe the methods. Readers are referred to the U.S. DOE (2017), IEAGHG (2013), Mathieson et al., (2011), Romanak et al., (2012), Metz et al. (2005), Wilson and Mosea (2004), and other similar documents for more detailed information on technology deployment for CO_2 monitoring.

Table 2-3. CO_2 Storage Monitoring Technology Cost Benefit Metrics.

Name	Description	Monitored Zone	Equipment	Pre-/Post Processing requirements	Frequency	Domain	Accuracy/ Resolution	TRL/Field Applications	Coverage	Unit Costs	Risk Category	Advantages	Limitations
2D surface seismic	2D linear image for site characterization and time-lapse monitoring to survey potential changes due to CO2 injection	Surface/Near-Surface/Reservoir	Seismic sensors, source arrays, and sources (vibrator trucks/vibrator systems)	Baseline surveys, geocharacteriztion, and multiple data processing events	Frequency dependent on monitoring plan	X, Z	1 – 5m	Specialized, research oriented	50m-1 km	$1.0M/km	Capacity, Containment, Contingency, Mitigation	Site characterization prior to injection and time-lapse monitoring to survey potential changes due to CO_2 injection. Identification of potential fractures and faults in the subsurface.	small scale faults with offsets >10 m are not detectable, lacks full surface coverage
3D surface seismic	3D data on storage and reservoir characterization and time-lapse monitoring to survey CO2 distribution and migration	Surface/Near-Surface/Reservoir	Seismic sensors, source arrays, and sources (vibrator trucks/vibrator systems)	Baseline surveys, geocharacteriztion, and multiple data processing events	Frequency dependent on monitoring plan	X,Y, indirectZ	1 – 5m	Specialized, research oriented	1-100 km2	$1.0M/km2	Capacity, Containment, Contingency, Mitigation	Full site characterization of overburden and storage zones. Monitor CO2 migration in the well Identification of potential fractures and faults in the subsurface.	small scale faults with offsets >10 m are not detectable, requires extensive data processing
Airborne EM	Air surveys to detect electrical conductivity variations in earth materials as indicator of CO2	Surface/Near-Surface: Soil, intermediate zones	Airplane, EM coil array	Baseline, post injection, processing & interpretation of difference	Annual or greater	XY	10-50% change, 100s sq. meters perturbations	Specialized, research oriented	10s-100s km2	$10K/survey	Contingency, Mitigation, Public Acceptance	Covers large area, non-invasive	Limited depth penetration to 100s of meters, requires large CO2 storage plume
Airborne spectral imaging	Air surveys to detect spectral signal vegetative stress as indicator of CO2 leakage from the ground	Atmospheric/Surface: Soil, atmosphere	Airplane survey, hyperspectral imager	Baseline, post injection, processing & interpretation of difference	Annual or greater	XY	10-50% change, 100s sq. meters	Specialized, research oriented	10s-100s km2	$10K/survey	Contingency, Mitigation, Public Acceptance	Covers large area, non-invasive	Natural CO2 variations, false positives
Annulus Pressure testing	Tests designed to pressure annuls space and measure pressure drop to ensure well integrity and prevent casing leaks	Near-Surface/Reservoir: Wellbore system	Pressure gauge on wellhead	Simple test	Annual	Z (well system)	Usually 5-10% pressure drop over several hours	Mature, common	Point	$1k/test	Contingency, Mitigation	Direct test, low-cost	Limited to well system, not continuous test
Boomer/Sparker profiling	2D sub-bottom water profiling used for site characterization and to detect changes due to injected CO2	Surface/Near-Surface/Reservoir	Vessel, source/hydrophone array, ship explosives, vessel and crew	Baseline, post injection, processing & interpretation of difference	Initial, annual or greater	X, Z	0.2 - 1m	Mature, common	20-750 m	$1.0M/km	Capacity, Containment, Contingency, Mitigation	Provides continuous mapping of shallow sediment layers, structural changes due to CO2 migration and leakage, high peak frequencies and large bandwidth for higher resolution	Limited tow capability, high voltage/high current, boomer plates are large and constrain towing
Borehole EM	Images changes in electrical resistivity signal from induction source and receiver array due to saturation changes between wells or shallow soil zone	Surface/Near-Surface/Reservoir	At least two wells with string array of electrodes attached to well casing	Baseline, post injection, processing & interpretation of difference	Continuous, annual or greater	XZ (interwell)	10-50% change, square meter resolution	Specialized, research oriented	200-1000 m (interwell)	$200k/km	Capacity, Containment	Focused on reservoir zone, more accurate than some other seismic methods, lower processing	Only covers interwell cross section zone, subject to interpretation, requires high CO2 saturation, non-conductive pipe
Borehole ERT	Images changes in electrical resistivity signal between 2 electrodes due to saturation changes between wells or shallow soil zone	Surface/Near-Surface/Reservoir	Electric source, downhole receiver array, at least 2 wells	Baseline, post injection, processing & interpretation of difference	Annual or greater	XZ (interwell)	10-50% change, square meter resolution	Specialized, research oriented	100 m (interwell)	$200k/km	Capacity, Containment	Focused on reservoir zone, more accurate than some other seismic methods, lower processing	Only covers interwell cross section zone, requires closely spaced wells, permanent installation, subject to interpretation, requires high CO2 saturation, non-conductive pipe
Bubble stream chemistry	Measures dissolved gases and chemistry of water to detect potential CO2	Surface/Near-Surface: Ground water and seafloor	Vessel or team of sampling units, samples, laboratory testing	Baseline and continuous sampling	Initial and continuous	XYZ	ppm	Mature, common	Specified zones and depths	$10K/test	Containment, Contingency, Mitigation	Provides dissolved gas and other chemistry of specific zones of interest. Can determine minor and major leakage.	Frequent sampling is needed to monitor containment of CO_2. Does not measure over an entire area so several samples from different locations are necessary for analysis.
Bubble stream detection	High frequencies used to measure seafloor and create acoustic images of seafloor to determined potential pits created by CO2 leakage	Surface: Seafloor	Vessel, echosounders, processing	Baseline, post injection, processing & interpretation of difference	Initial, annual or greater	X Z	1-5m	Mature	50 m	$750k/km	Containment, Contingency, Mitigation	Detailed high images created of seafloor which can detect deformation changes and density changes due to CO2	Extensive seafloor mapping required in order to example baseline and repeat data. Minor leaks can go undetec+B16:O17ted due to resolution of technology
Casing Inspection logs	Downhole survey of well materials for indication of defects	Surface/Near-Surface/Reservoir: Wellbore system	Caliper, flux, sonic, EM, or noise logging tool	Processing and Interpretation of results	Annual or greater	Z (well system)	+/- 1 m within well	Mature, common	Well	$10k/well	Containment	Straight forward test, can show precursors of corrosion, failure	Periodic test, well must be shut-in, interupts operations
Casing pressure monitoring	Monitoring pressure on casing annulus for casing leaks	Surface/Near-Surface/Reservoir: Wellbore system	Annulus pressure system and pressure gauge	Direct monitoring	Continuous	Z (well system)	0.01 Mpa	Mature, common	Well	$10k/well	Containment	Direct test, low-cost, often regulatory requirement	Limited to well system, does not provide location of defect
Cement bond logging	Acoustic log that provides evaluation of cement/casing to measure well integrity and zone isolation	Surface/Near-Surface/Reservoir: Wellbore system	Wireline vendor and service rig	Baseline, post injection, processing	Initial, annual or greater	Z (cement/casing)	3 cm	Mature, common	15 cm	$10k/well	Containment	Simple quantitative method for analyzing cement quality and inferring compressive strength	Limited to only evaluating cement bonding to the casing. Does not provide imaging between cement and formation. Does not evaluate low density cement.
Corrosion Monitoring (well materials)	Inspection and/or corrosion tickets in wells to detect any corrosion of well materials	Surface/Near-Surface/Reservoir: Wellbore system	Coupons, mechanical, ultrasonic, and electromagnetic tools	Interpretation of results	Annual or greater	Z (well system)	+/- 1 m within well	Mature, common	Well	$10k/well	Containment	Straight forward test, can show precursors of corrosion, failure	Periodic test, well must be shut-in, interupts operations
Crosswell Seismic	Inter-well seismic profiling to measure structural changes due to CO2 injection	Surface/Near-Surface/Reservoir: Between wellbores	Wireline vendor, service rig, source and receiver arrays	Baseline survey, processing of periodic surveys to show difference	Yearly	X, Z	1 – 5m	Specialized, research oriented	0.5-1 km	$200k/km	Capacity, Containment, Contingency, Mitigation	Subsurface monitoring of injection of CO_2 plumes. Estimate rock and fluid properties. Identification of potential fractures and faults in the subsurface.	Source strength is limited by the distance between wellbores. Presence of gas in the well can reduce detection of CO_2. Geologic complexity and noise interferences can degrade seismic data. The maximum distance between wells is dependent on casing.
Distributed Acoustic Sensing	Laser light pulses from permeant downhole fiber optic cables seismic profiling that measures reservoir and caprocks to determine structural changes due to CO2 injection and reservoir integrity	Surface/Near-Surface/Reservoir: Proximal to wellbore	Vendor, fiber optics, permeant onsite data acquisition	Continuous	Continuous	XYZ	10m	Specialized, research oriented	4-5 km (depending on receivers)	$500K Well	Capacity, Containment, Mitigation	Provides continuous monitoring of the well site and can be used to detect changes due to CO2 injection	A large amount of data is produced from this technology and requires extensive and costly processing. Can cause integrity issues if not installed correctly

Table 2-3 cont. CO_2 Storage Monitoring Technology Cost Benefit Metrics.

Name	Description	Monitored Zone	Equipment	Pre-/Post Processing requirements	Frequency	Domain	Accuracy/ Resolution	TRL/Field Applications	Coverage	Unit Costs	Risk Category	Advantages	Limitations
Distributed Temperature Sensing	Linear fiber optic cables that measures changes in temperature to detect/monitor temperature indicators of CO2	Surface/Near-Surface/Reservoir: Proximal to wellbore	Vendor, fiber optics, permeant onsite data acquisition	Continuous	Continuous	XYZ	0.01 - 0.05 °C	Specialized, research oriented	3 km	$500K Well	Containment, Mitigation	Provides continuous temperature monitoring and migration CO2	A large amount of data is produced from this technology and requires extensive and costly processing. Can cause integrity issues if not installed correctly
Downhole fluid chemistry	Provides fluid chemistry from reservoir zones to determine CO2 migrations and analyze reservoir conditions	Reservoir	Wireline/slickline vendor with bailer, laboratory services	Baseline and regular repeat sampling, laboratory testing	Initial and quarterly to annual	X (Target Interval)	ppm for entire reservoir interval	Mature, common	Entire sampled interval	$10k/well	Containment, Contingency, Mitigation	Formation fluids can be collected directly from the zone of interest	Fluid sampling in high risk wells is a potential hazard, fluid around sampler may be in two-phase condition, mechanical failure of sampler due to pressures and fluid present
Downhole pressure/temperature	Continuous temperature and pressure measurements to monitor reservoir integrity and CO2 migration	Reservoir	Wireline/slickline vendor with bailer, laboratory services	Direct monitoring	Continuous	X (Target Interval)	+/- 0.25 °C 0.005 °C	Mature, common	25 cm	$10k/well	Injectivity, Containment, Contingency, Mitigation	Continuous inplace monitoring, batteries can potentially last up to a year	Gaskets can corrode over time and cause gauge malfunctioning,
Ecosystems studies	Survey of vegetation for stress or damage caused by CO2 leakage	Atmospheric/Surface: Soil, atmosphere	Visual survey, inspection, flyover of CO2 storage area	Baseline survey, regular repeat surveys	Quarterly to Annual	XY	Indirect, sq. meters	Mature, common	Km2s	$1000s/km2	Contingency, Mitigation, Public Acceptance	Low impact technology, non-invasive, simple	Requires significant CO2 migration to detect leakage, not suitable for areas without vegetation, qualitative
Eddy covariance	Measurement of air flow and CO2 concentrations to detect CO2 leakage at the surface	Atmosphere	Stationary or mobile observation towers	Baseline, post injection, processing & interpretation of difference	Continuous	XY	umol/m2*s	Specialized, research oriented	100 sq meters to sq kilometers	$10,000s/ point	Contingency, Mitigation, Public Acceptance	Low impact technology, non-invasive, can cover wide areas, high visibility	Natural CO2 variations, false positives, sensitive to humidity, temperature
Electric Spontaneous Potential	Measures mineral and clay compositions, and can show porosity mineralogical changes near wellbore which can be used to indicate potential wellbore integrity	Reservoir: Wellbore	Wireline vendor and service rig	Baseline, well schematics and geochemistry, post injection, processing & interpretation of difference	Initial and quarterly to annual	X, Z (wellbore)	±6%	Mature, common	30 - 40 cm	$60k/well	Capacity, Containment	Measures mineral and clay compositions, and can show porosity mineralogical changes near wellbore which can be used to indicate potential wellbore integrity	high clay and salinities are necessary for optimal functionality of the tool
Fluid geochemistry	Fluid measurements to determine rock-CO_2 interactions, monitor CO2 migration and storage integrity/breach of CO2	Reservoir: Wellbore	Wireline vendor and service rig	Baseline and regular repeat sampling, laboratory testing	Initial and quarterly to annual	X (Target Interval)	ppm for entire reservoir interval	Mature, common	Entire sampled interval	$20k/well	Capacity, Containment, Contingency, Mitigation	Formation fluids can be collected directly from the zone of interest or at the wellhead to analyze multiple zones of interest and	Fluid sampling in high risk wells is a potential hazard, fluid around sampler may be in two-phase condition, mechanical failure of sampler due to pressures and fluid present
Geophysical Density Logs	Measures wellbore densities to determine lithology and potential, changes and identifies CO_2 breakthrough and is used to analyze wellbore integrity	Surface/Near-Surface/Reservoir: Wellbore	Wireline vendor and service rig	Baseline survey	Initial	X, Z	1 g/cm^3	Mature, common	25 cm	$50k/well	Capacity, Containment	Measures densities to determine lithology changes near wellbore which can be used to indicate potential wellbore integrity	susceptible to borehole rugosity/washouts and types of drilling muds. Erroneous lithology data due to averages between drastically different density lithology changes
Geophysical Pulse Neutron Capture logs	Measures wellbore fluid saturation (oil/gas/water), changes and identifies CO_2 breakthrough and is used to analyze wellbore integrity	Surface/Near-Surface/Reservoir: Wellbore	Wireline vendor and service rig	Baseline, well schematics and geochemistry, post injection, processing & interpretation of difference	Initial and quarterly to annual	X, Z (wellbore)	±6%	Mature, common	30 - 40 cm	$50k/well	Capacity, Containment	Fluid saturation of cased wells, porosity indicator, can show porosity changes near wellbore which can be used to indicate potential wellbore integrity	Fluid behind casing, cannot differentiate between various gases, high porosities and salinities are necessary for optimal functionality of the tool
Global Positioning System	Satellite technique that provides epochs with displacement measurements for ground deformation related to CO2 storage	Surface/Near-Surface	Receiver, GPS antenna, power supply, pseudolites, pressure gauges, and satellite system	Baseline survey, periodic surveys	Monthly-Yearly	X,Y, indirect	mm-scale	Mature, research oriented	10s-100s km2	$1k/km2	Containment, Mitigation, Public Acceptance	Measures displacement in proximity or area of CO_2 reservoir	Temporal sampling may be limited, land use and access, atmospheric effects, satellite orbit coverage
Ground penetrating radar	Geophysical method that processes reflection of high freq. radio waves to image features in the shallow subsurface	Surface/Near-Surface: Shallow soil and groundwater	GPR system (source/cart, data logger, software) and/or crosswell groundwater wells	Baseline survey, operational survey, post-injection, processing/interpretation of raw GPR results	Yearly	XZ (shallow GW)	Indicator of CO2 through CO2 desaturation	Mature, moderately common	km2s	$10,000s/km2	Contingency, Mitigation, Public Acceptance	Low impact technology, non-invasive	Requires significant CO2 migration to detect leakage, may be subject to interpretation bias, not suitable for low CO2 levels, limited to ~15 m depth, certain sediments affect accuracy
Groundwater monitoring	Sampling and analysis of shallow groundwater wells for indicators of CO2 leakage and/or brine displacement	Surface/Near-Surface: Shallow groundwater quality	Shallow gw wells, sampling equipment, lab analysis	Baseline samples, interpretation of gw quality indicators,	Monthly-Yearly	Z (shallow GW)	mg/L or greater	Mature, common	km2s	$1000s/event	Containment, Contingency, Mitigation, Public Acceptance	Direct monitoring of groundwater resources, high visibility monitoring, easy to communicate to stakeholders, understandable results	Relies on indicators of CO2 (pH, anions, cations, alk., TDS), false positives, needs good baseline data, may require significant CO2 migration to detect leakage
High resolution acoustic imaging	Acoustic full-waveform sonic to measures and images structural features and changes that occur due to CO2 injection	Reservoir: Wellbore	Wireline vendor and service rig	Baseline survey, regular repeat surveys	Frequency dependent on monitoring plan	X, Z (wellbore)	15 cm	Mature, moderately common	3 m	$50K/well	Containment, Contingency, Mitigation	Direct imaging and monitoring of borehole structures and changes due to CO2 injection	susceptible to borehole rugosity/washouts which will create poor quality images.
Land EM	Electrical resistivity signals used to measure from induction source and receiver array due to CO2 saturation between wells or shallow soil zone	Surface/Near-Surface/Reservoir: Reservoir or soil	At least two wells with string array of electrodes attached to well casing	Baseline, post injection, processing & interpretation of difference	Continuous, annual or greater	XZ (interwell)	10-50% change, square meter resolution	Specialized, research oriented	200-1000 m (interwell)	$100ks/survey	Capacity, Containment, Contingency	Focused on reservoir zone, more accurate than some other seismic methods, lower processing	Only covers interwell cross section zone, subject to interpretation, requires high CO2 saturation, non-conductive pipe
Land ERT	Electrical resistivity measurements to determine changes in structure and water saturations due to CO2 injection	Surface/Near-Surface/Reservoir: Ground water and subsurface	Seismic sensors, source arrays, and sources (vibrator trucks/vibrator systems)	Baseline surveys, geocharacteriztion, and multiple data processing events	Frequency dependent on monitoring plan	X, Z	1 – 5m	Specialized, research oriented	Dependent on arrays, lithology, and depth of investigation	$100ks/survey	Capacity, Containment, Contingency	Site characterization prior to injection and time-lapse monitoring to survey potential changes due to CO_2 injection. Identification of potential fractures and faults in the subsurface.	small scale faults feature offsets >10 m are not detectable, lacks full surface coverage

Table 2-3 cont. CO_2 Storage Monitoring Technology Cost Benefit Metrics.

Name	Description	Monitored Zone	Equipment	Pre-/Post Processing requirements	Frequency	Domain	Accuracy/ Resolution	TRL/Field Applications	Coverage	Unit Costs	Risk Category	Advantages	Limitations
Long-term downhole pH	Optical sensors in casing that measures chemical changes due to CO2 changes	Surface/Near-Surface/Reservoir: Wellbore	Vendor, fiber optics, permeant onsite data acquisition	Continuous	Continuous	X,Z	.01 unit	Specialized, research oriented	30 - 40 cm	$100K/well	Containment, Contingency, Mitigation	Provides continuous pH monitoring and migration CO2, works in highly saline waters, good for high pressure and temperature environments	This is a near wellbore technology and provides data within specified installation zone.
Microseismic/Seismic Activity Monitoring	Passive technique for monitoring and identifying downhole fractures and microseismic events	Surface/Near-Surface/Reservoir: Reservoir and above	Borehole geophones, monitoring station, solar charge panels, strong-motion-sensor	Baseline survey, analysis of data to estimate location of seismic event	Continuous	X, Y, Z seismic activity	500m	Mature, moderately common	5-20 km2	$250K/km2	Containment, Contingency	Can monitor fracture properties from downhole, surface to subsurface. Time-lapse monitoring to survey migration of CO_2 plumes. Identification of potential fractures and faults in the subsurface.	Moderate changes in dip perturbation or velocity changes can cause errors in velocity models. Low and high frequency signals can affect mechanism inversion.
Multibeam echo sounding	Sonar emitted by a vessel that measures distances and topography of the seafloor to determine surface changes due to CO2	Surface/Near-Surface/Reservoir: Seafloor	Vessel, sonic source, hydrophones, antenna	Baseline, post injection, processing & interpretation of difference	Initial, annual or greater	X, Y Z	0.2 - 1m	Mature	20-750 m	$250K/m2	Containment, Contingency	Provides continuous mapping of shallow sediment layers, structural changes due to CO2 migration and leakage	Minor deformation is not detected due to resolution limitations.
Multicomponent surface seismic	3D compressive and shear waves use to measure fluid changes and structural monitoring to survey CO2 distribution and migration	Surface/Near-Surface/Reservoir: Reservoir and above	Seismic sensors, source arrays, and sources (vibrator trucks/vibrator systems)	Baseline surveys, geocharacteriztion, and multiple data processing events	Frequency dependent on monitoring plan	X,Y, indirect	1 – 5m	Specialized, research oriented	Dependent on arrays, lithology, and depth of investigation	$750K/km	Containment, Contingency	Full site characterization of overburden and storage zones. Monitor CO2 migration in the well Identification of potential fractures and faults in the subsurface.	small scale faults with offsets >10 m are not detectable, requires extensive data processing
Non dispersive IR gas analysers	Gas meter that measures CO2 concentrations in air based on IR spectroscopy	Atmosphere	Gas meter, data logger system	None	Continuous	XY	PPM	Mature, common	100 sq meters	$100s/pt	Containment, Contingency, Public Acceptance	Direct measurements, simple technology, high visibility, easy to communicate	Natural CO2 variations, false positives
Operational Monitoring	CO2 injection flow rates, pressure, temperature, density, composition monitoring	Reservoir	Gauges and flowmeters	Direct measurements	Continuous	Point	0.1 psi, BBL/Min	Mature, common	Point	$10k/pt	Capacity, Injectivity	Monitor injection performance for pressure drops and flow variations	Limited to injection well
Produced Gas/Fluid Analysis	Gas/fluid sampling & analysis to determine CO_2 interactions, monitor CO2 migration and storage integrity	Reservoir: Wellbore	Coriolis meter, laboratory testing	Baseline and regular repeat sampling, laboratory testing	Initial and quarterly to annual	X (Target Interval)	ppm for entire reservoir interval	Mature, common	Entire sampled interval	$20k/well	Containment, Contingency, Mitigation	Formation samples can be collected directly from the zone of interest or at the wellhead to analyze multiple zones of interest	Fluid sampling in high risk wells is a potential hazard, fluid around sampler may be in two-phase condition, mechanical failure of sampler due to pressures and fluid present
Satellite interferometry/INSAR	Satellite-based technique that provides topographic images of site surface area to measure surface deformation	Surface/Near-Surface	Satellite, reflector stations	Baseline survey, multiple satellite passes for survey verification	Monthly-Yearly	X,Y, indirect	mm-scale	Mature, research oriented	10s-100s km2	$10k/km2	Containment, Contingency, Public Acceptance	Monitoring injection of CO_2 in the subsurface at carbon sequestration test sites.	Level terrain, minimal land use, atmospheric effects, and satellite orbit coverage
Seabottom EM	Images changes in electrical resistivity signal from induction source and receiver array measures surface changes due to CO2	Surface/Near-Surface	Vessel, source and several receiver strings	Baseline, post injection, processing & interpretation of difference	Continuous, annual or greater	XYZ	10-50% change, square meter resolution	Mature, common	20-750 m	$500K/km	Containment, Contingency	Provides continuous mapping of seafloor structural changes due to CO2 migration and leakage, high peak frequencies and large bandwidth for higher resolution	Limited tow capability, high voltage/high current and constrain towing
Seabottom gas sampling	Sampling at the sediment-seawater interface to measure density changes due to CO2	Surface/Near-Surface: Sediment/water Interval	Sampling units, samples, laboratory testing	Baseline and continuous sampling	Initial and continuous	X	ppm	Mature, common	Specified intervals	$20k/survey	Containment, Contingency, Mitigation, Public Acceptance	Provides dissolved gas and other chemistry of specific zones of interest. Can determine minor and major leakage.	Frequent sampling is needed to monitor containment of CO_2. Does not measure over an entire area so several samples from different locations are necessary for analysis.
Seawater chemistry	Measures temperature, pressure and chemistry of water to detect changes due to CO2	Surface/Near-Surface: Seafloor	Vessel or team of sampling units, samples, laboratory testing	Baseline and continuous sampling	Initial and continuous	Point	ppm	Mature, common	Specified zones and depths	$20k	Containment, Contingency, Mitigation	Provides dissolved gas and other chemistry of specific zones of interest. Can determine minor and major leakage.	Frequent sampling is needed to monitor containment of CO_2. Does not measure over an entire area so several samples from different locations are necessary for analysis.
Sidescan sonar	Sonar emitted from autonomous underwater vehicles that measure distances and topography of the seafloor to determine surface changes due to CO2	Surface/Near-Surface: Seafloor	Vessel, AUV, echosounders	Baseline, post injection, processing & interpretation of difference	Initial, annual or greater	X, Y Z	0.2 - 1m	Mature	20-750 m	$500K/km	Containment, Contingency	Provides continuous mapping of shallow sediment layers, structural changes due to CO2 migration and leakage, high peak frequencies and large bandwidth for higher resolution	Minor deformation is not detected due to resolution limitations.
Single well EM	Images changes in electrical resistivity signal from induction source and receiver array due to CO2 saturation proximal well or shallow soil zone	Surface/Near-Surface/Reservoir: Reservoir or soil	One well with string array of electrodes attached to well casing	Baseline, post injection, processing & interpretation of difference	Continuous, annual or greater	XZ (interwell)	10-50% change, square meter resolution	Specialized, research oriented	200-1000 m (interwell)	$100ks/survey	Capacity, Containment, Contingency	Focused on reservoir zone, more accurate than some other seismic methods, lower processing	Only covers interwell cross section zone, subject to interpretation, requires high CO2 saturation, non-conductive pipe
Soil gas concentrations	Monitoring of soil gas composition to detect increases in CO2 levels or other indicators of CO2 leakage	Surface/Near-Surface: Shallow soil zone	Soil gas monitoring points, gas collection equipment, analytical lab services	Baseline, post injection, processing & interpretation of difference	Monthly-annual	XY	PPM	Mature, common	100 sq meters to sq kilometers	$1,000s/pt	Containment, Contingency, Mitigation, Public Acceptance	Direct measurements, simple technology, high visibility, easy to communicate	Natural CO2 variations, false positives
Surface gas flux	Monitoring CO2 flux and chemistry as indicator of CO2 leakage from reservoir	Surface/Near-Surface: Shallow soil zone	Gas flux chambers, gas collection equipment, analytical lab services	Baseline, post injection, processing & interpretation of difference	Monthly-annual	XY	mmol/m2/s	Mature, common	100 sq meters to sq kilometers	$1,000s/pt	Containment, Contingency, Mitigation, Public Acceptance	Direct measurements, simple technology, high visibility, easy to communicate	Natural CO2 variations, false positives

Table 2-3 cont. CO_2 Storage Monitoring Technology Cost Benefit Metrics.

Name	Description	Monitored Zone	Equipment	Pre-/Post Processing requirements	Frequency	Domain	Accuracy/ Resolution	TRL/Field Applications	Coverage	Unit Costs	Risk Category	Advantages	Limitations
Surface gravimetry	Surface survey of gravimetric changes caused by CO2 storage	Reservoir	Gravity survey system or permanent gravity stations	Baseline, post injection, processing & interpretation of difference	Annual or greater	XY	10-50% change	Mature, research oriented	10s-100s km2	$1000s/km2	Capacity, Containment	Low impact technology, non-invasive, can cover wide areas, high visibility	Low resolution, requires large volumes of CO2, subject to interpretation
Surface Safety/Gas Meters	CO2 gas meters near surface equipment to monitor releases	Atmosphere	CO2 gas meters	None	Continuous	XY	PPM	Mature, common	100 sq meters	$1,000s/pt	Containment, Contigency, Mitigation	Direct measurements, simple technology, high visibility, easy to communicate	Limited to injection site, only provides notice of large equipment failures
Tiltmeters	Inclinometer technology which measures deviation from horizontal and vertical plane	Surface/Near-Surface	Tiltmeter and Monitoring Station	Baseline survey, periodic surveys	Continuous	X,Y, indirect	microradian	Mature, research oriented	1-50 km2	$1k/km2	Containment, Contingency, Mitigation	Measure surface deformation in proximity to injection sites	Land access, data collection, spurious changes due to temperature and rainfall
Tracers	Introduction of PFT tracers into injection stream and monitoring in soil gas points for indications of leakage	Atmospheric/Surface: Soil, atmosphere	Soil gas monitoring points, gas collection equipment, analytical lab services	None	Monthly-Annual	XY	Parts per trillion as indicator	Specialized, research oriented	100 sq meters to sq kilometers	$10,000s/pt	Containment, Contingency, Public Acceptance	Direct measurements, simple technology, high visibility, easy to communicate	Requires careful sampling, false positives possible, requires significant CO2 migration to detect leakage
Vertical seismic profiling (VSP)	Seismic profiling that images reservoir and caprocks to determine saturation changes due to CO2 injection	Surface/Near-Surface/Reservoir: Proximal to wellbore	Wireline vendor, service rig, source and receiver arrays	Baseline survey, processing of periodic surveys to show difference	Yearly	X, Z	10 – 30m	Specialized, research oriented	0.5-1 km	$1.0M/km	Capacity, Containment	Site characterization prior to injection and time-lapse monitoring to survey migration of CO_2 plumes. Identification of potential fractures and faults in the subsurface.	Presence of hydrocarbons or high salinity. Must verify that potential historical sites are not damaged during logging. 450 m distance limitation.
Water bottom sediment sampling	Sampling at the seabed sediment for geochemical indicators of CO2	Surface/Near-Surface: Sediment/water Interval	Sampling units, samples, laboratory testing	Baseline and continuous sampling	Initial and continuous	X	ppm	Mature, common	Specified intervals	$20k	Containment, Contingency, Mitigation	Provides dissolved gas and other chemistry of specific zones of interest. Can determine minor and major leakage.	Frequent sampling is needed to monitor containment of CO_2. Does not measure over an entire area so several samples from different locations are necessary for analysis.

Overall, these metrics provide a systematic description of the monitoring technologies. However, it is difficult to absorb all this information in tabular format. Consequently, a rating system was prescribed for each field based on monitoring technology benefit (Table 2-4) and plotted in radar plots. The radar plots provide a quick-look review of the monitoring options. The ratings are intended to be general in nature. There are limitations to the descriptions, because site specific conditions may affect costs, accuracy, and field application. However, the plots provide indicator of the more favorable options based on all the various metrics defined for the monitoring technologies. In addition, the plots depict some of the disadvantages of certain technologies in respect to other options.

Figures 2-5A through 2-5C shows the radar plots of the CO_2 storage monitoring technology ratings. The plots provide a "quick look" review of the fields used to express the cost-benefit for the monitoring methods. The more circular plots with higher ratings for the metrics have higher overall benefits, while the smaller circle plots indicate a technology with more specialized application. There is no single technology with maximum benefits and low costs. Some of the more fundamental technologies like operational monitoring, downhole pressure/temperature monitoring, and well integrity related monitoring show higher ratings. Many safety related monitoring technologies also show high benefit ratings in the plots.

Table 2-4. Methodology for rating monitoring technology metrics.

Cost Benefit Rating	**Low Benefit**		**-------------->**			**High Benefit**
Name	**1**	**2**	**3**	**4**	**5**	**6**
Description	experimental	high tech	med tech	moderate	basic tech	simple
Monitored Zone/Variable	undefined	indirect	semi-direct	direct	safety	multiple
Equipment	developmental	high	med-high	medium	med-low	low
Pre-/Post Proc. Reqs	developmental	high	med-high	medium	med-low	low
Frequency	single	5-10 years	yearly	monthly	daily	continuous
Domain	undefined	point	1D (z)	2D (xz, xy)	3d (xyz)	4D (xyzt)
Accuracy/ Resolution	undefined	low	med-low	medium	med-high	high
TRL/Field Application	0	1-2	3-4	5-6	7-8	9-10
Range/Coverage	undefined	cm	meters	10s meters	100s meters	kms
Costs	$1,000,000s	$100,000s	$10,000s	$1,000s	$100s	$10s
Unit Costs	developmental	$100,000s	$10,000s	$1,000s	$100s	$10s
Advantages	developmental	low	med-low	med	med-high	high
Disadvantages	developmental	high	med-high	medium	med-low	low

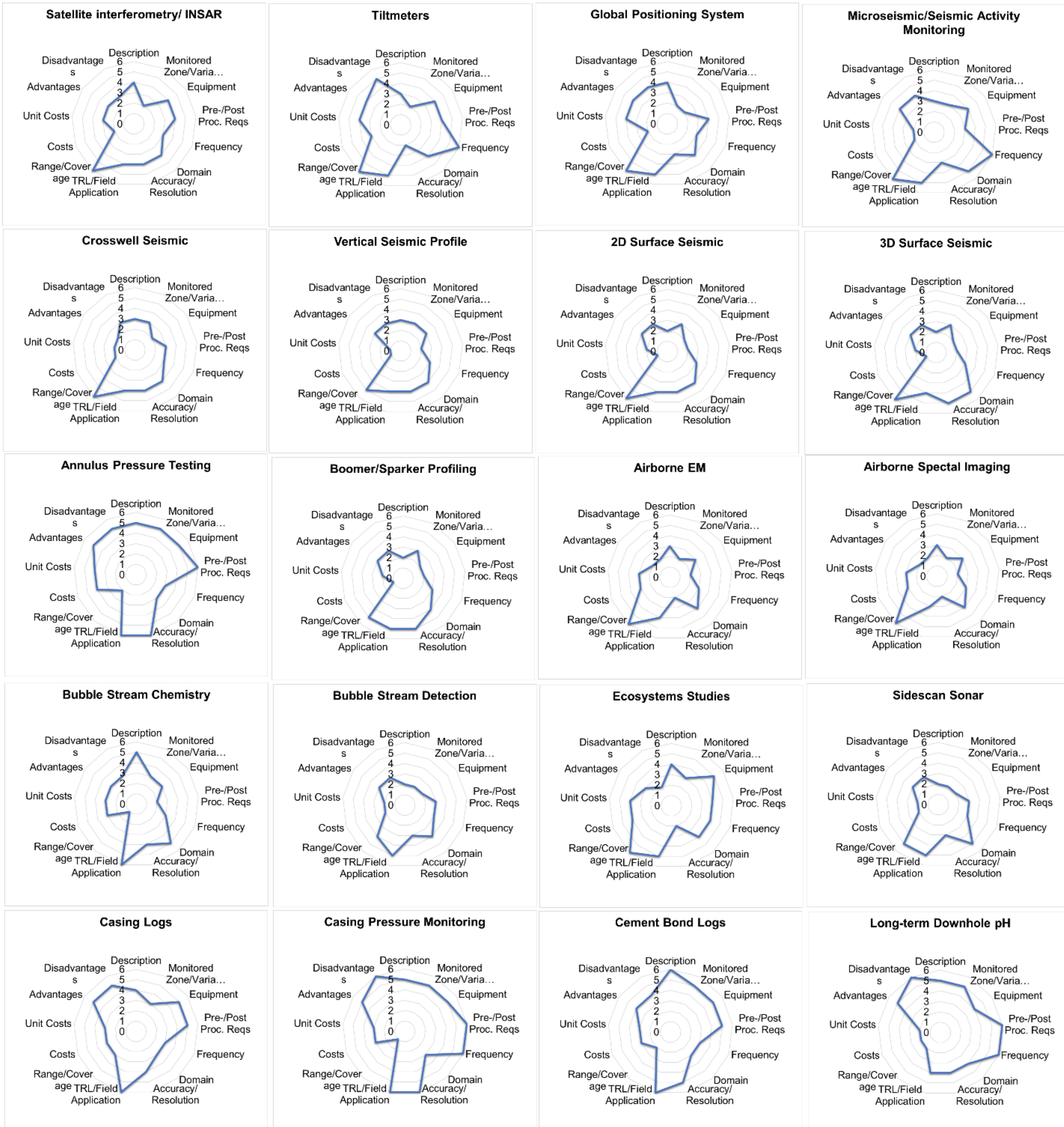


Figure 2-5A. Radar plots for surface/near-surface CO_2 storage monitoring technology cost-benefit metrics.

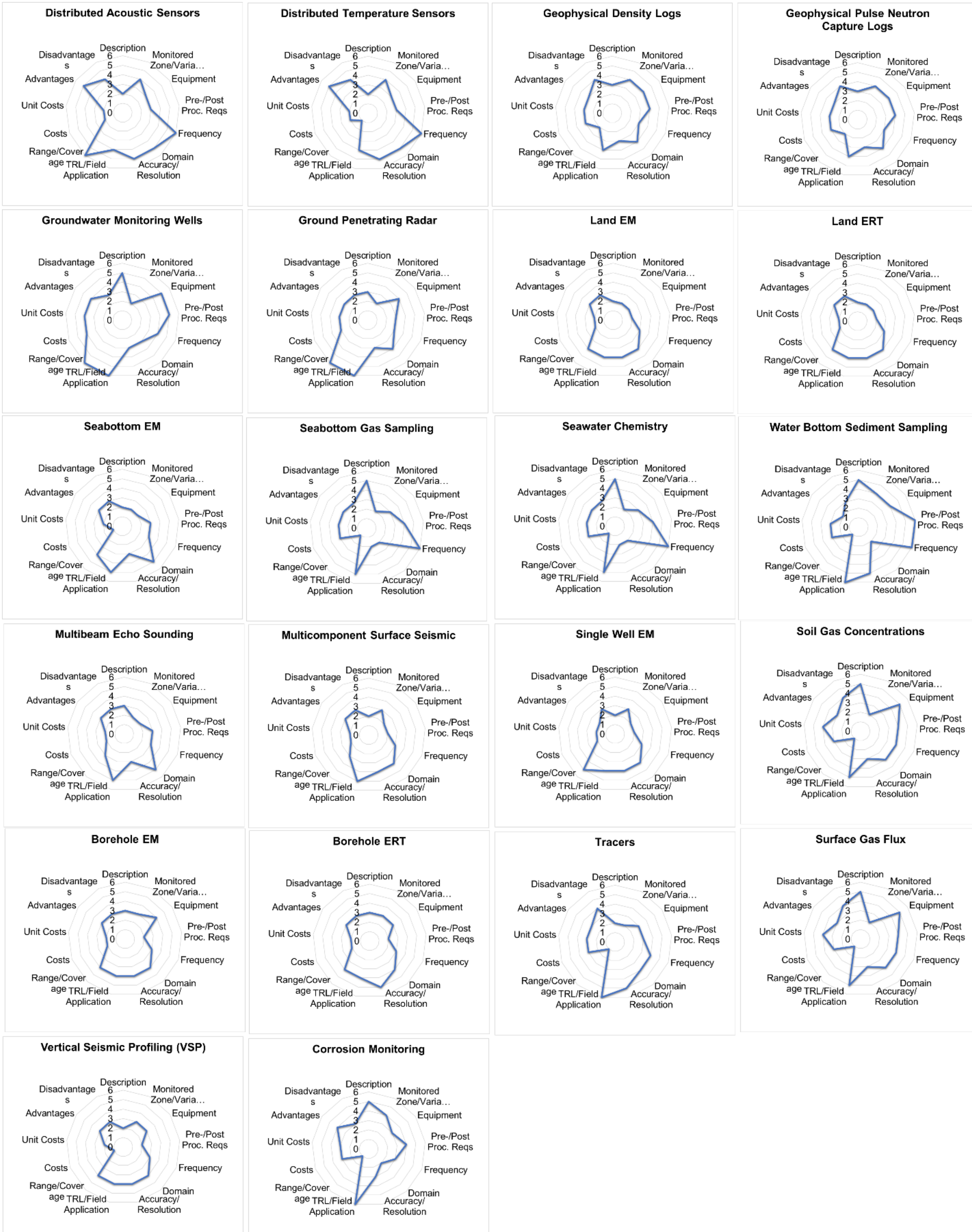


Figure 2-5A continued. Radar plots for surface/near-surface CO_2 storage monitoring technology cost-benefit metrics.

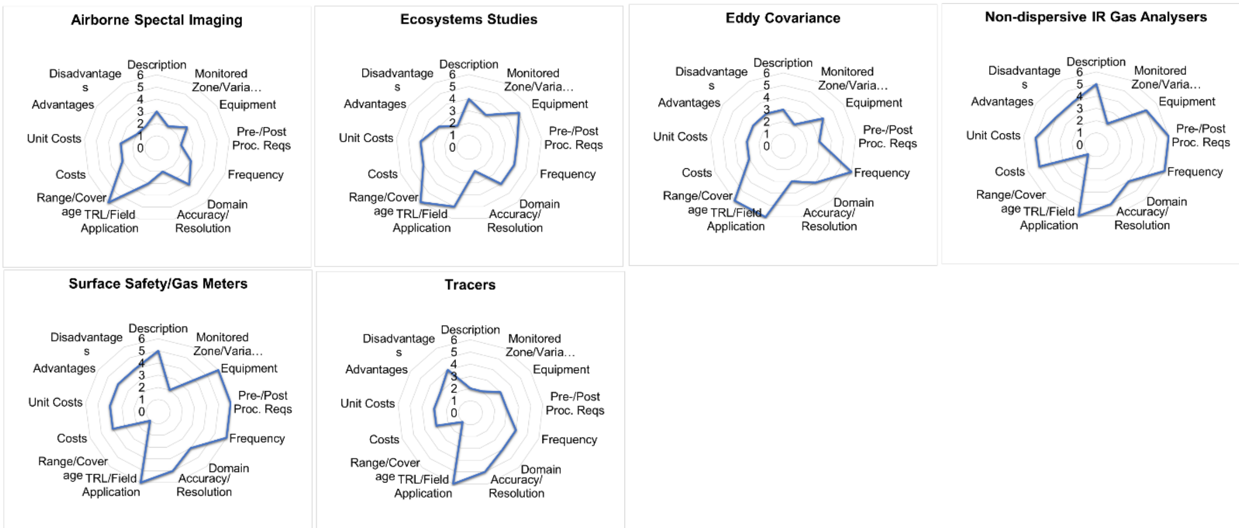


Figure 2-5B. Radar plots for atmospheric CO_2 storage monitoring technology cost-benefit metrics.

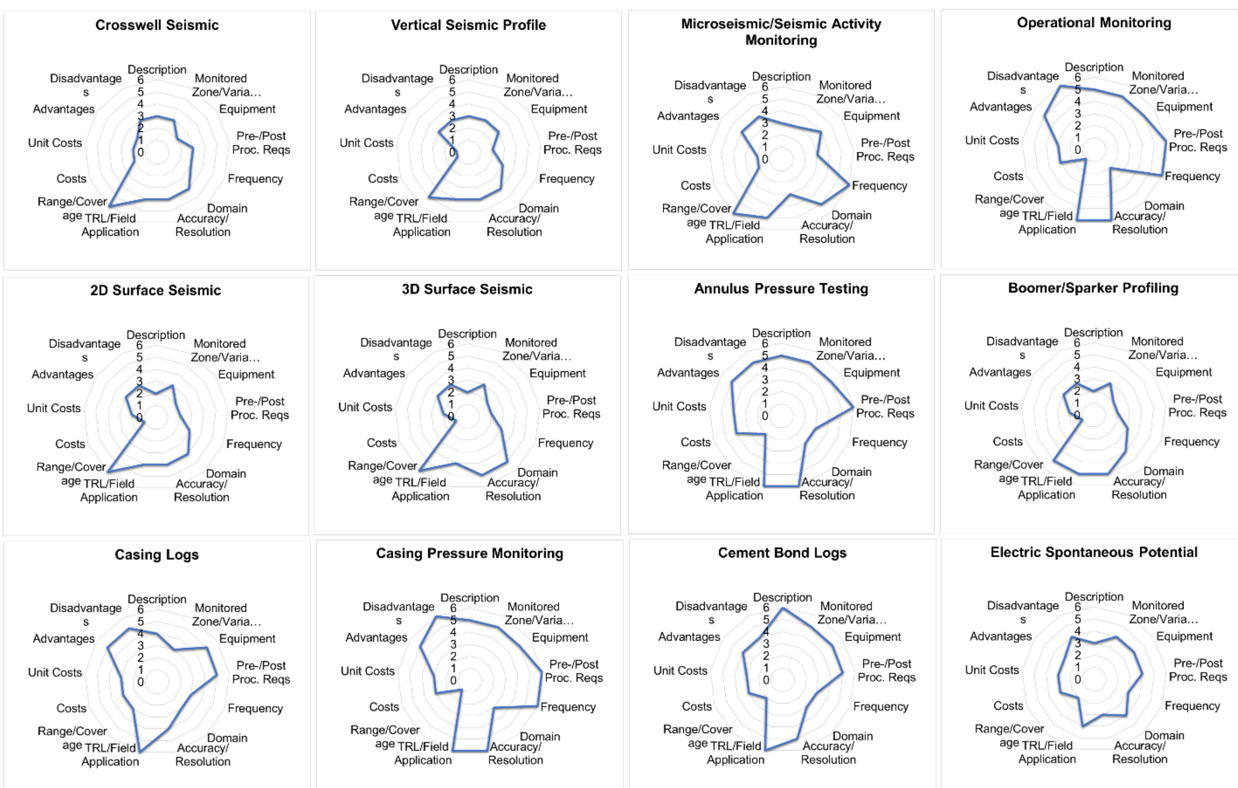


Figure 2-5C. Radar plots for reservoir CO_2 storage monitoring technology cost-benefit metrics.

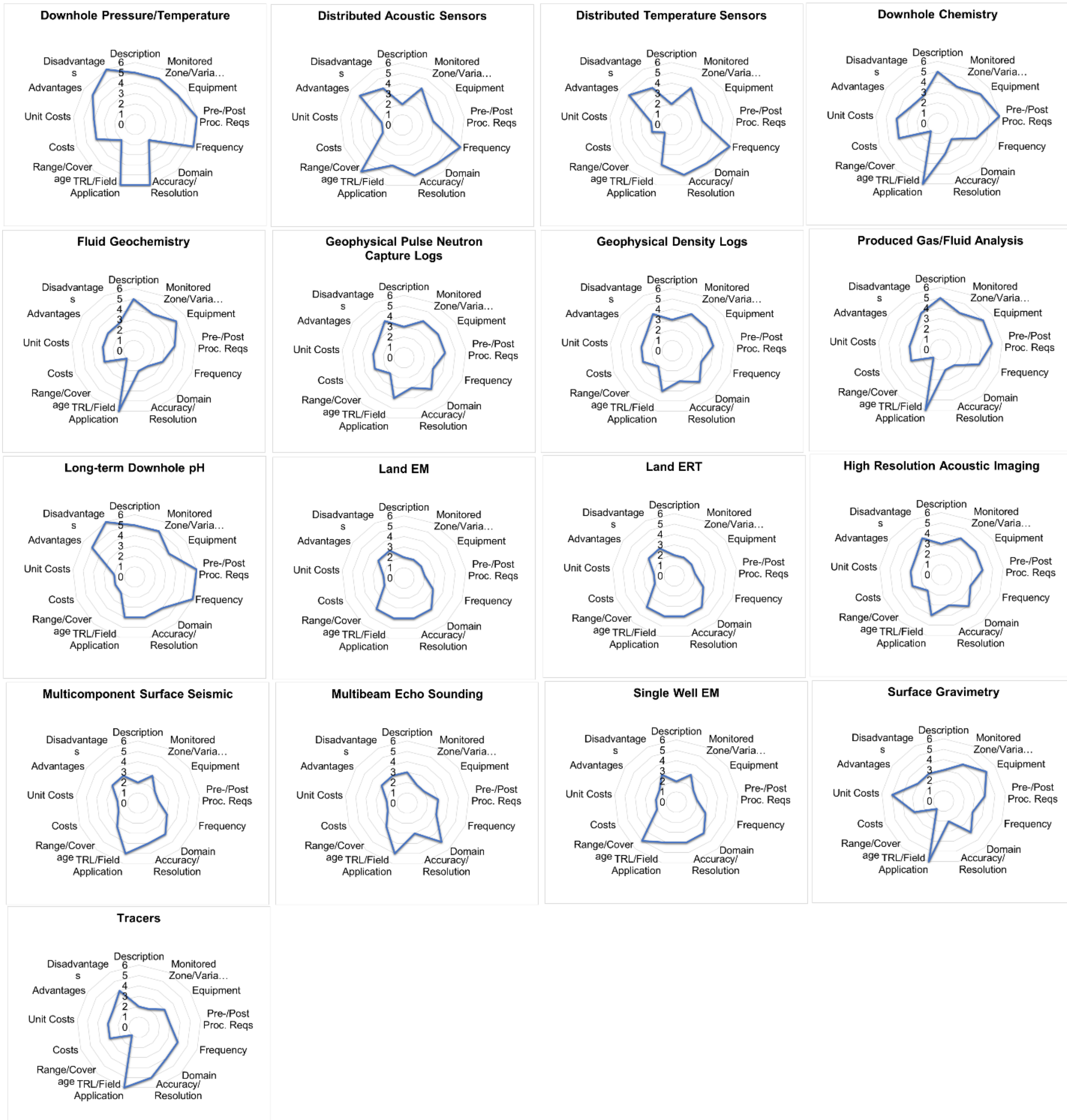


Figure 2-5C continued. Radar plots for reservoir CO_2 storage monitoring technology cost-benefit metrics.

2.5 Review of Modelling-Monitoring Integration

Simulation of geologic CO_2 storage requires the consideration of interdependent processes to represent the behaviour of fluids in the injection formation. Analysis of CO_2 injection scenarios for CCS projects have drawn upon insights from decades of research on multiphase flow in porous media. Geologic and dynamic reservoir models feature in the entire lifecycle of CCS projects, right from site selection during the project planning to site closure. While the broader objectives for CO_2 storage modelling have historically been to predict and representatively capture the determined injectivity, capacity and fate of CO_2 in the subsurface, the types of numerical simulations and modeling designs are guided by three key considerations:

- Project phase
- Objectives/ simulation needs
- Available data and complexity

Model designs range from pore-scale models to single-well models to regional-scale models depending on their desired role per the above three considerations. To accurately and reliably apply models, combinations of four fundamental subsurface processes: Thermal Hydrological Mechanical Chemical and Biological (THMCB) must be included at different appropriate scales, both spatial and temporal. Considerations while designing the models include capturing larger areal extent to capture long-term system behaviour, overlying zones such as surface to formation for system integrity and geomechanical effect considerations, and longer time scales for post-injection monitoring of system behaviour.

There are four major types of models depending on the complexity of data and analysis involved. Table 2-5 summarizes their limitations and examples of their application in CCS projects. The four model types are:

- Analytical and semi-analytical models: Highly simplified analytic and semi-analytical formulations to estimate specific performance parameters such as maximum plume extent and CO_2 injectivity and provide insights into the underlying dynamics. These are generally utilized for rapid, preliminary estimates of performance applied under idealized assumed subsurface conditions.
- Proxy models: A proxy model is a set of functions that can understand and replicate the effect of change in input parameters on output parameters, analyzing a limited number of simulation runs on the real model. Many proxy models have been developed for probabilistic risk analysis applications such as for leakage scenario analysis etc.
- Simplified equivalent numerical models: Representative performance, capturing all significant features and fundamental processes of the subsurface system. Used when data availability or computational power restrictions feature in the project phase.
- Detailed full 3D numerical models: High resolution, dictated by the processing power available, multi-physics heterogeneous 3D subsurface models of the storage system of interest. These models incorporate the highest level of detail to setup the model and involve the highest computational resource requirements for its evaluation as well. Despite being extremely energy and cost intensive, scarcity of detailed site-specific data is generally the key prohibitor in the usage of these models.

Table 2-5. Summary table for modelling applications.

Model types	Application examples	Limitations/ *Recommendations*
Analytical or semi-analytical models	1. MRCSP (Midwest Regional Carbon Sequestration Partnership) Phase II: Analytical methodology using brine disposal well operational data to infer formation characteristics such as transmissivity and storativity 2. Saripalli and McGrail, 2002: Semi-analytical model based on the Buckley-Leverett theory for radial injection of CO_2 in a confined aquifer 3. Nordbotten and Celia, 2010: Analytical solution for plume extent 4. Sharp interface models: Hesse et al., 2008	Generally simplified in 1D, not covering reality which is 3D; applicability dependent on relevance of system-related simplifying assumptions such as symmetry, boundary conditions, homogeneity, constant fluid properties, single-phase flow, used while deriving original models. *Suitable for simple or localized analyses and as guides for planning purposes typically in early CCS project phases when scarce system-specific data is available.*
Proxy models	1. NRAP-IAM-CS: Integration of ROMs to assess long-term, site-scale containment/ leakage performance of the CO_2 storage complex 2. Jordan et al., 2015: Response surface model to predict CO_2 and brine leakage along cemented wellbores 3. Ravi Ganesh and Mishra, 2015: Simplified physics model for CO_2 plume extent in stratified aquifer-caprock systems	Applicability restricted to parameter ranges that the model was trained upon during development; can yield non-physical results. *Suitable for simple or localized analyses with homogeneous reservoir parameters, conditions, and dimensions.*
Simplified equivalent numerical models	1. Guo et al., 2014: Vertically integrated models developed and applied to Sleipner data 2. Kolster et al., 2018: Bunter sandstone injection scenario modelling 3. Szulczewski et al., 2012: Allowable injection rates as a function of time for potential injection basins in the United States using simplified cartesian-based models for plume and pressure evolution 4. Ravi Ganesh et al., 2018: Reservoir feasibility assessment to evaluate volumetric and dynamic CO_2 storage capacity in the Appalachian Basin region of the U.S.A 5. Simplified analysis of pressure buildup in deep saline injection formations: Zhou et al., 2008, 2009; Birkholzer et al., 2009	Not all physics fully captured in models, simplifying assumptions and neglected parameters in models need to be justified based on site-specific conditions. *Suitable for overall behaviour modelling and response prediction in CCS projects where detailed model parameter distributions are not available.*
Detailed full 3D numerical models	1. Sleipner CO_2 plume modelling to using seismic data 2. Illinois Basin (Person et al., 2010) 3. Ketzin, Frio, Cranfield, Futuregen permit models by Pacific Northwest National Laboratory (PNNL)	Long runtimes; high computational power requirements; high input data resolution. *Suitable for later CCS project phases as more data becomes available.*

Illinois carbon storage project modelling - A number of key studies presented simplified numerical model versions of geologic carbon sequestration in the Illinois Basin. The Mount Simon and Lower Knox Group Formations were the target consideration for CO_2 storage within the Illinois Basin, USA. Different modelling efforts essentially tried to model CO_2 injection and storage in this basin. Person et al., 2010 used basin-scale vertical equilibrium model with the additional assumption of a macroscopic sharp interface separating the injected supercritical CO_2 and formation brine to model injection of CO_2 in the Mt. Simon Formation. The authors used 726 injection wells located in the vicinity of 42 power plants to inject 80 Mt CO_2/yr for 100 years of injection. The Person et al., 2010 Mount Simon- Eau Claire model treated the Mount Simon sandstone as a single layer with intrinsic porosity and permeability varying linearly with depth. Bandilla et al., 2012 used vertical equilibrium model approach as well, without the assumption of a macroscopic sharp interface, to model the injection of a total of 250.5 Mt at 118 sites, located mostly at the CO_2 source sites, over a period of 50 years. A broader portion of the stratigraphic column was considered in this study with the Mount Simon sandstone, Lower Knox Group and Ordovician units considered the aquifers while the Eau Claire and Upper Knox Group seal being considered the aquitards. Their model consisted of a stack of two-dimensional subdomains connected by leakage through the aquitards which separate the aquifers. Two conceptualizations of the injection target formation i.e. Mount Simon were used: one where the Mount Simon is represented by one monolithic formation (simple model), and one where the Mount Simon is divided into seven sub-layers (refined model).

Birkholzer and Zhou, 2009 used the parallel version of the TOUGH2/ECO2N simulator to model the impact of 100 Mt CO_2 annually among 20 injection sites into the Mount Simon sandstone in the Illinois Basin. The authors used a three-dimensional unstructured mesh TOUGH2 model to capture heterogeneity in the near-well regions of the injection formation with simplified petrophysical properties in the far-field regions and the caprock formation due to lack of detailed data. Zhou et al., 2010 worked with a similarly comprehensive three-dimensional numerical model in TOUGH2-MP/ECO2N to integrate large-scale processes such as basin-scale pressure buildup and brine migration, along with plume-scale processes in the stratified sedimentary storage formation.

While the maximum pore pressures and lateral radial extent of the pressure envelope are qualitatively consistent with each other, the pressure-responses predicted by the Person et al., 2010 model were generally more localized than those predicted by Birkholzer and Zhou, 2009 and Zhou et al., 2010 due to their different choices of compressibility values in the models, with the model by Person et al., 2010 using a higher compressibility. Bandilla et al., 2012 predicted a much larger radial extent for several of the CO_2 plumes mainly due to the higher permeability and smaller thickness of the injection formation in their multi-layer model version. Hence the vertical equilibrium approach was seen to work well for pressure response prediction but had a significant impact on the areal extent of the CO_2 plumes in these basin-scale simulation studies. Figure 2-6 shows the CO_2 saturation plumes modeled at the end of injection and the end of post-injection monitoring periods.

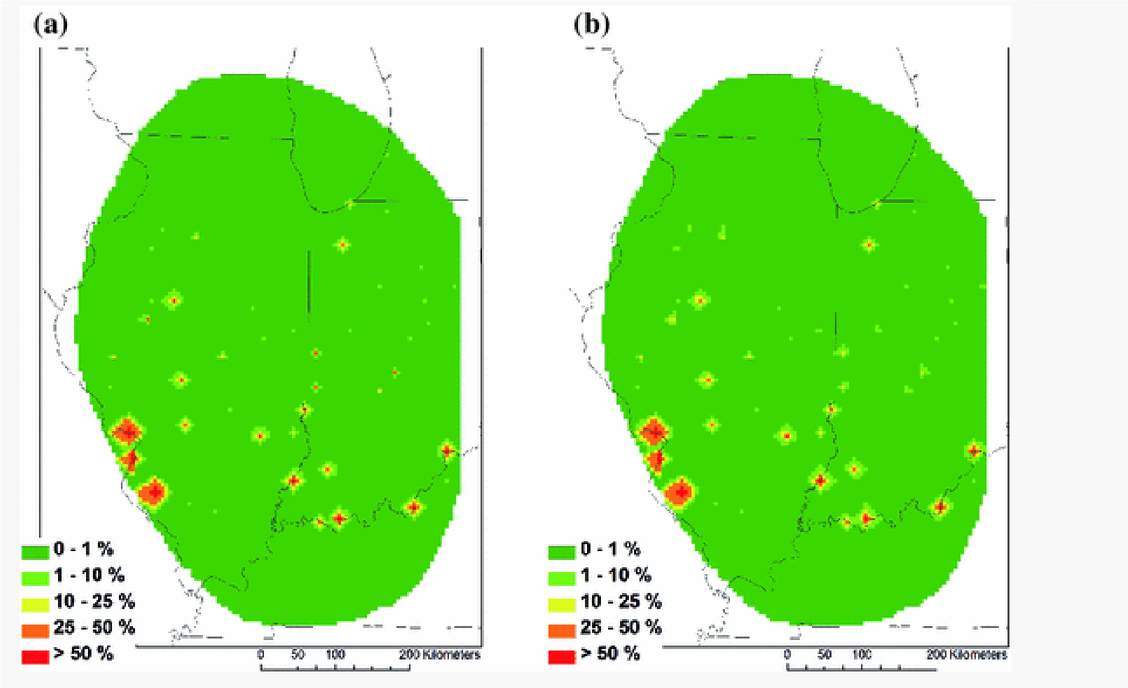


Figure 2-6. CO_2 saturation simulated in the Arkosic Unit of the Mount Simon based on the refined stratigraphy model after a) 50 years, b) 100 years [Bandilla et al., 2012].

Monitoring data such as continuous pressure monitoring data both within and above the injection zone in the verification well and the time-lapse RST data has been used to calibrate the reservoir simulations. Integrated modelling monitoring has enabled qualitative and quantitative calibration of modeling results, so the project has robust, history-matched reservoir simulations that predict CO_2 and pressure development over time (Coueslan et al., 2014). The authors mention that microseismic data interpretation found this integrated approach particularly important as it showed that the observed microseismic activity is associated with fluctuations in the pressure front plume rather than the CO_2 plume. Modelling helps to constrain the pressure limit and the extent to which pressure management and fluid extraction and re-distribution might be necessary, especially at industrial scales of 50M+ t. A good example is large-scale pressure management in the Illinois basin (Bandilla and Celia, 2017).

Sleipner CCS Project modelling **-** Sleipner injection is about 1 MT CO_2/yr into the highly porous and permeable Utsira saline formation (~ 35% porosity and 2D permeability) with more than 16 Mt CO_2 injected since 1996. This is the oldest and most well-known geologic CO_2 injection operation where the Norwegian oil company Equinor is injecting CO_2 separated from produced natural gas from their Sleipner oil and gas field in the North Sea into approximately 800 m deep into the Utsira formation in the North Sea. Monitoring and modelling data from the Sleipner CO_2 project have been widely shared for a wide range of applications including improving reservoir characterization, constraining flow modelling, and developing new techniques for seismic inversion and spectral decomposition (Furre et al., 2017).

Sleipner injection occurs via a deviated well into the sandstone formation that has a number of thin intra-reservoir mudstones, typically 1–2 m thick, that have been determined to be partially sealing. Nine repeated seismic surveys have been conducted that have contributed to a wealth of knowledge on subsurface dynamics and containment. The areal distribution of the CO_2 stored between nine interpreted mudstone layers within the site has thus been precisely mapped from the seismic surveys (Chadwick et al., 2006). In 2011, the top-most layer (ninth) was made available to the scientific community as a benchmark problem to test different modelling approaches. Vertical equilibrium modelling (Bandilla et al., 2014) produced satisfactory results for the ninth layer behaviour. Bandilla et al., 2014 compared simulation results between vertical equilibrium simulations with a finite capillary transition zone with a sharp interface and the three-dimensional simulator TOUGH2 to determine the impact of model complexity on the modeled CO_2 plume at Sleipner. They noted the higher computational demands of the TOUGH2 simulator. The authors also identified the subtle importance of the definition of the residual saturation for the brine and the functional form of the relative permeability function as the residual is approached as part of the comparison. In general, results from several modelling studies such as Singh et al., 2010, Chadwick and Noy, 2010, Cavanagh, 2013, Zhu et al., 2015 found it difficult to fully match and explain the observed time-lapse seismic due to challenges in both understanding the underlying physics of the CO_2 flow in the system as well as geologic uncertainty. Cavanagh and Haszeldine, 2014 present modelling based on percolation-physics and capillary flow that provides a better mass balance estimate and plausible CO_2 distribution pattern in this subsurface system. They postulate pervasive pre-existing small-scale fractures in the shale barriers resulting in very low effective threshold pressures for vertical migration explains the multiple thin layers of thin CO_2. Figure 2-7 shows their modeled results of CO_2 migration at the Sleipner site. Williams et al., 2018 define and characterize an isothermal heterogenous reservoir and compare Darcy-based flow simulators, both numerical and analytical, to also show excellent agreement in modelling the observed upward flux of CO_2 and CO_2 saturation distribution consistently between the codes.

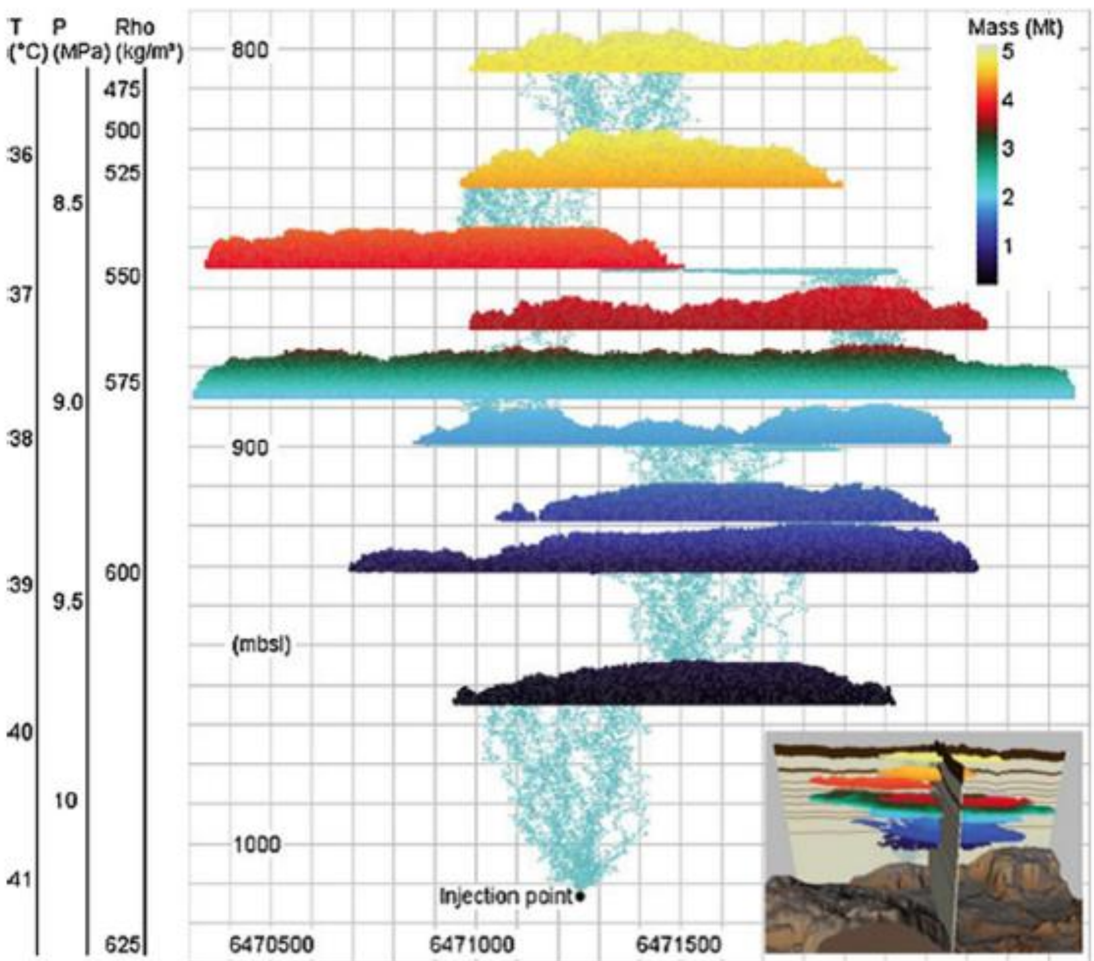


Figure 2-7. Simulation CO_2 migration at the Sleipner injection site using an alternative flow physics model [Cavanagh and Haszeldine, 2014].

Other allied modelling included reactive transport modelling by Audigane et al., 2007. Johnson et al., 2004 performed geochemical modelling to show that at the Sleipner site geochemical changes to reservoir parameters such as porosity and permeability are unimportant. Zhang et al., 2017 modeled layer 9 to simulate plume migration dynamics and uncertainty analysis on short- and long-term migration of CO_2 in this layer. The authors applied a multi-phase compositional simulator to the Sleipner Benchmark model and constructed a 1D multi-phase, coupled reactive mass transport modelling, respectively. The study illustrates technology developments in seismic acquisition, processing to image CO_2 and benchmark reservoir models.

An abundance of modelling studies as well as field experiences have thus helped improve our understanding of the geophysical processes associated with geologic carbon sequestration. While the site-specific modelling discussed above was mostly focused on addressing the broader risk categories of containment and injectivity, there have also been basin-scale and sub basin-scale CO_2 capacity modelling studies around the world such as the CarbonSAFE and Regional Carbon Sequestration Partnership programs in the United States (Jahadiesfanjani et al., 2017 for basin-scale in saline Mount Simon formation; Ravi Ganesh et al., 2018 for site-specific in sub-Knox formations in the Appalachian Basin region of the United States). Containment also features the evaluation of caprock in the system of interest e.g. Vilarrasa et al., 2015.

For contingency, risk mitigation and public acceptance, there have been CO_2 Leakage models addressing the quantitative and qualitative evaluation of both well leakage as well as surface leakage pathways in the sites of interest. Over the past decade, field-scale shallow controlled release experiments have been conducted with varying geologic, surface and experimental conditions in order to develop our scientific understanding of the environmental impacts of CO_2 while assessing the applicability of monitoring techniques. Roberts and Stalker, 2017 summarize the collective experiences and learnings from 42 different CO_2 release tests that have taken place at 14 sites around the world.

Research into wellbore integrity has been focused on characterization of pre-existing leakage pathways through the cemented zone and developing reactive transport models to match the laboratory or field data. Bielicki et al. 2016 have developed a quantitative analysis to model the leakage risk and associated costs based on data and the practical models resulting from previous studies in deep saline aquifers. One of their major findings is that, even at unrealistically high well permeability, leaked CO_2 is very unlikely to be released to the atmosphere because of the interception by overlying geologic strata, which was termed as "secondary trapping." To address pertinent operational concerns related to pressure increase due to injection, as it carries an associated risk of fault reactivation and leakage, modelling as part of Active CO_2 Reservoir Management (ACRM) included efforts such as reduction of leakage potential in a study by Birkholzer et al., 2012, who simulated use of production wells to regulate pressure build-up along a fault zone, and reduction in the area of review in a study by Bandilla et al., 2012, who considered different production scenarios for a site-scale model based on the Mount Simon Formation.

CCS projects have successfully integrated monitoring and modelling for a competent operational performance feedback loop as improved understanding of the system of interest helps evaluate and accordingly guide operating and monitoring strategy. For example, at the AEP Mountaineer CCS product validation facility, predictions using history-matched simplified numerical modelling helped in site closure related permitting as the post-injection monitoring period was reduced from 20 years to approximately 5-years leading to significantly reduced project costs and liability to owner/ operator (McNeil, 2014; Mishra et al., 2014). Quest project modelling involved four scales of models to assess the risks associated with containment which were used in the evaluation of the operating strategy and their MMV plan (Duer, 2017). Experiences from Ketzin highlight the importance of geological heterogeneity on migration of the injected CO_2 (Lengler et al., 2010). To predict the pattern of plume migration in the far-field, 25 realisations of channel distributions were generated based on the petrophysical properties of the near-field. The modelling suggest that there could be significant uncertainty in the arrival time of CO_2 and as much as 10,000 tonnes (15% of the total mass injected) could be present as free CO_2. (Monitoring Network and Environmental Research Network – Combined Meeting, 2013-15). The Ketzin project demonstrated that the applied monitoring techniques were able to detect the CO_2 plume and that the predictions of numerical models were significantly improved by including early monitoring data (Kempka and Kuhn, 2013). At the Frio site, Texas, a small-scale CO_2-injection was passively monitored at a nearby up-dip well (Doughty et al., 2008) using fluid sampling, tracers, well logs and cross-hole seismics. This study demonstrated the importance of combining different measurements for better characterization and the integration of these in a flow and transport model for the field site.

Allied modelling insights into the CCS subsurface dynamics include numerical evaluation of time-dependent storage efficiency and hence dynamic storage capacity by Gorecki et al., 2015. Nordbotten and Celia, 2012 provide a complete discussion of characteristic length and time scales associated with the geologic CO_2 sequestration problem. Information and discussion about coupling flow and geomechanics are available in Rutqvist et al., 2002, Dean et al., 2006, Kim et al., 2011a,b, and Mikelic and Wheeler, 2012. Johnson et al., 2004 discusses fundamental considerations for miscible reactive fluid transport of CO_2 in saline aquifers. Based on the extensive understanding of the flow and transport mechanisms both modeled and observed for the CO_2-brine system, there are potentially applicable complexities associated with important couplings to geomechanics, local-scale geochemistry, and nonisothermal effects similar to multiphase multicomponent systems. At the same time, there are also several judicious simplifying assumptions that can be and have been applied to answer broader questions such as pressure response to injection, delineation of Areas of Review, and long-term fate of the injected CO_2. While the application of coupled geomechanical and geochemical simulations to CO_2 storage is mostly premature due to lack of adequate characterization data, overall fruitful advances have been made for modelling capabilities and applications to answer important practical questions related to CO_2 storage in deep saline aquifers.

Model comparisons have been done by many, for example Pruess et al., 2002 performed code comparison as part of GeoSeq project. Here all used fully coupled three-dimensional multi-phase flow simulators with direct or indirect coupling to geochemistry and geomechanics models. The comparison study brought out that all simulators tend to agree with each other with the main source of discrepancy that deserves significant attention were the different representations of fluid properties. The Stuttgart Benchmark Study (Class et al., 2009) as well as the Nordbotten et al., 2012 benchmark study used fully coupled three-dimensional multiphase flow simulators as well as vertically integrated simulators to focus on their respectively defined problems of interest related to CCS. Nordbotten et al., 2012 defined a benchmark problem and used it to examine the variability in different model predictions of varying levels of simplification using six research teams. Huang et al., 2014 who applied and compared models of varying complexities to the Canadian section of the mid-continent Basal Aquifer. While detailed data of the system of interest will remain a universal challenge for all CCS projects, comparative studies have shown that trade-offs must be made in accuracy and reliability of results while working within the constraints of available data and complexity desired to be handled in any CCS project. DOE Best Practice manuals provide guidelines based on collective CCS industry experience. Hence it is prudent to be aware of the limitations and applicability before designing and analyzing models for any CCS project objective. While models are valuable tools for increasing our understanding of the system of interest, they are not accurate predictors in isolation. A useful practical solution involves employing multiple model realizations for uncertainty quantification to produce risk-based probabilities of the CO_2 and pressure plume distribution which can be used to design a monitoring regime to address pertinent project risks. Industry experience shows that even highly idealized problems related to CO_2 storage projects have emphasized the need for real-time monitoring and history matching during injection operations (Nordbotten et al., 2012).

2.6 Cost/benefit analysis methods

Over the last few decades, CCS projects have typically been large-scale demonstration type projects that have been testing the applicability of various monitoring technologies in their respective geologic and operational environments. While the understanding of the technical and operational considerations for the implementation of the available monitoring technologies has been enriched, the criteria for preferential tool selection needs to satisfy both regulatory requirements as well as support tasks to address the six previously- identified risk categories. As the industry positions itself to implementing more commercial-scale projects, cost-benefit analyses of different monitoring technologies would be valuable in ranking and decision-making and should form a critical part of the considerations of the monitoring design plan for any geologic CO_2 storage project. In all the cost-benefit analyses, the costs are straight-forward and can be obtained by the individual operator's relevant field project experience. However, the estimation of benefits can be subjective and typically rely on subject matter expert consensus and professional judgement.

The QUEST project used a risk-based MVA plan for containment and conformance that has been refined over the years using lessons learned during project implementation phases. A key aspect of the design of this CCS monitoring plan involved the ranking of technologies based on their lifecycle cost-benefit estimates based on the monitoring tasks identified. Figure 2-8 shows the cost-benefit ranking matrix. Technologies with higher ranking values are considered more beneficial and less costly while the lower ranking values are less beneficial and more costly. In this approach, the metric used for estimating the total benefit for the monitoring technologies evaluated was the number of monitoring tasks they were applicable for weighted by their expected likelihood of success at each of them (Shell, 2010).

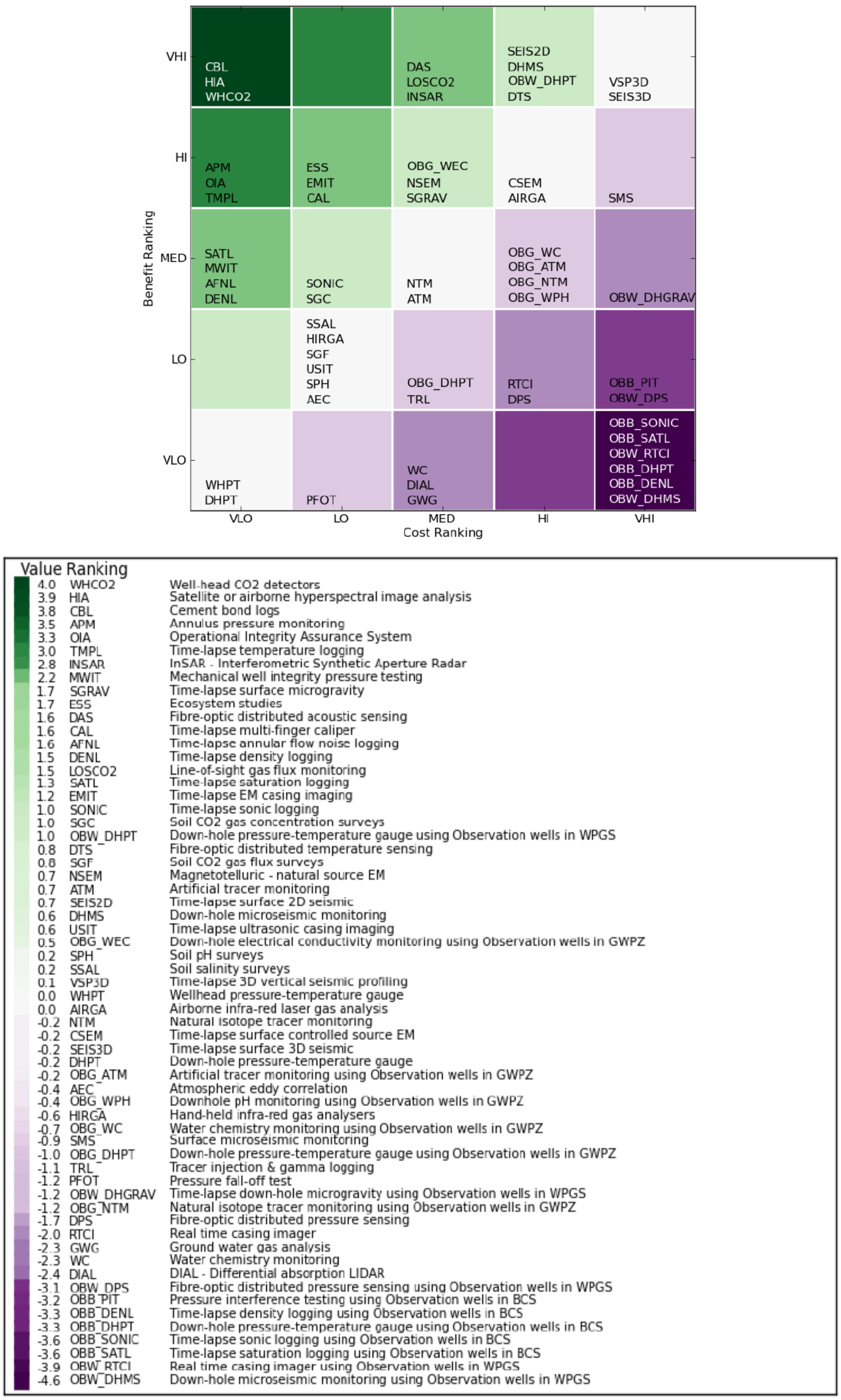


Figure 2-8. Cost-benefit ranking of monitoring technologies evaluated in the Shell QUEST CCS project [Shell, 2010]. Colours denote the difference between the benefit and cost rankings as an indicator of value.

The In Salah storage project in Krechba, Algeria applied the Boston Square approach to qualitatively evaluate the perceived cost-benefit of a suite of 29 required and desired monitoring technologies (Mathieson et al., 2011). In this approach, monitoring technologies are binned in four categories: a) Just do it, b) Consider, c) Park and d) Focused application and evaluated both during the monitoring plan design as well as subsequent to their deployment. While the costs represent the field-life cost of the monitoring technology, the benefits represent a subject evaluation of their effectiveness in fulfilling the project objectives (Wright et al., 2010). The right panel in Figure 2-9 shows the evaluation of their effectiveness subsequent to their deployment. The red line in the figure represents cost-effective tools to satisfy regulatory requirements that were determined to be affordable and beneficial in the project.

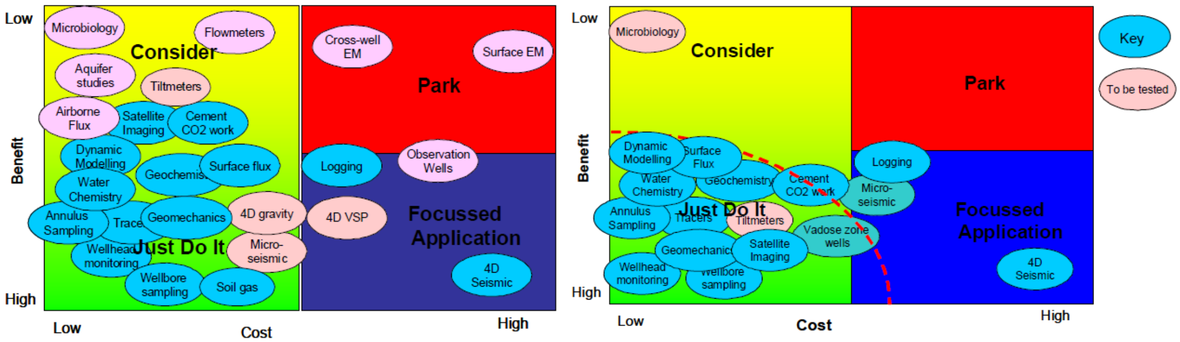
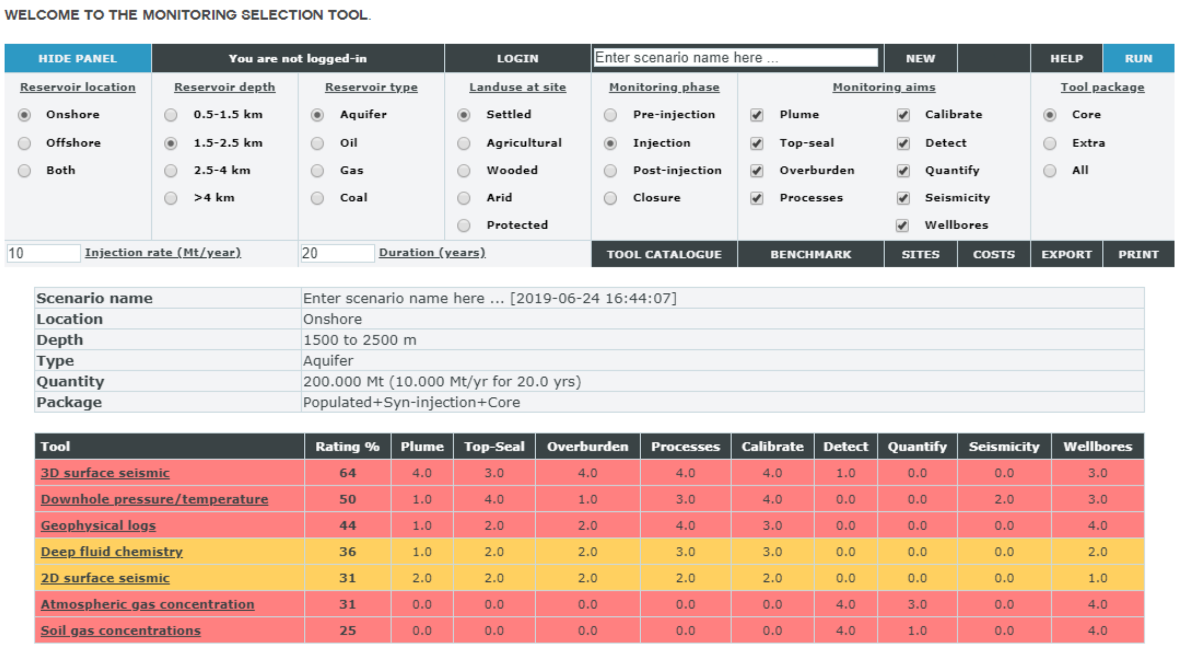


Figure 2-9. Boston Square approach applied for initial evaluation of monitoring technologies at In Salah (left panel). Right panel shows the final suite of deployed monitoring technologies [Wright et al., 2010].

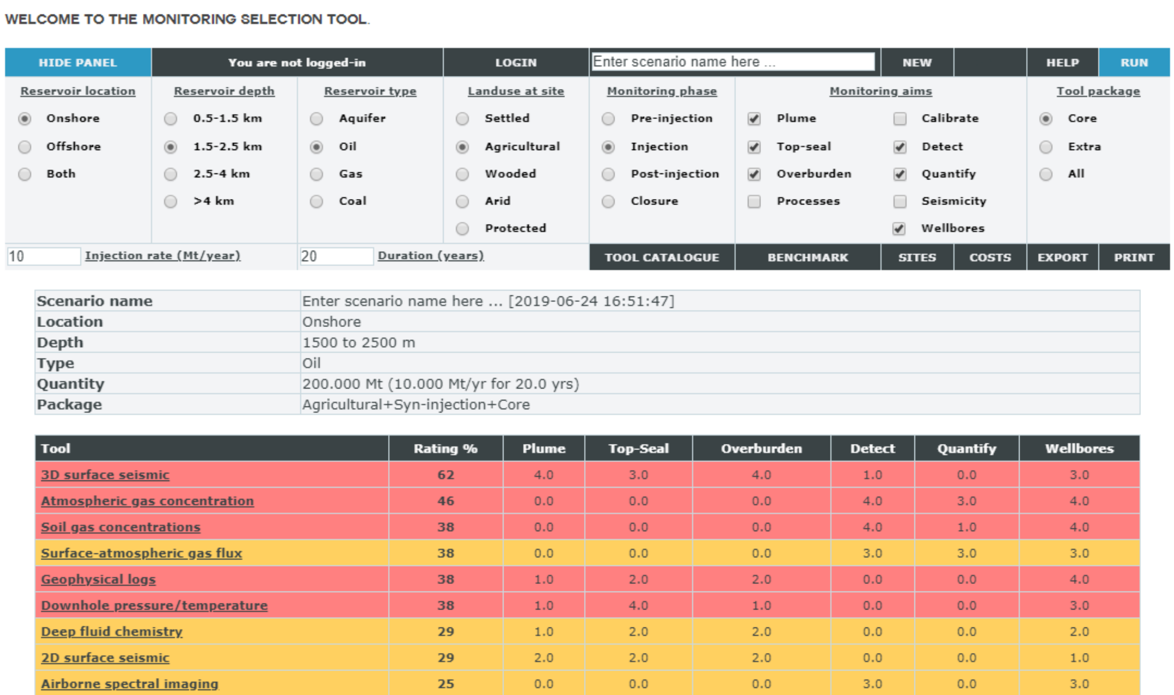
The IEAGHG monitoring selection tool is another application that serves to identify and evaluate suitable monitoring technologies for any given project and site characteristics by drawing upon an extensive library of case studies from a range of settings that forms the knowledgebase of experience with CO_2 monitoring technologies. It considers project phase and scale for the total intended duration and amount of storage as well as site characteristics such as depth of injection, target monitoring zones etc. In this approach, each monitoring technique is assigned a score, ranging from zero (not applicable) to four (strongly recommended), corresponding to the selected monitoring objectives in the IEAGHG tool. This total score is also normalized to the maximum possible score for the selected monitoring objectives to give a percentage "applicability" rating. Figures 2-10 and 2-11 show snapshots from the IEAGHG tool for monitoring tool ranking for a couple of large-scale projects at different project phases for comparison (Courtesy: https://ieaghg.org/ccs-resources/monitoring-selection-tool).



Scenario name	Enter scenario name here ... [2019-06-24 16:44:07]
Location	Onshore
Depth	1500 to 2500 m
Type	Aquifer
Quantity	200.000 Mt (10.000 Mt/yr for 20.0 yrs)
Package	Populated+Syn-injection+Core

Tool	Rating %	Plume	Top-Seal	Overburden	Processes	Calibrate	Detect	Quantify	Seismicity	Wellbores
3D surface seismic	64	4.0	3.0	4.0	4.0	4.0	1.0	0.0	0.0	3.0
Downhole pressure/temperature	50	1.0	4.0	1.0	3.0	4.0	0.0	0.0	2.0	3.0
Geophysical logs	44	1.0	2.0	2.0	4.0	3.0	0.0	0.0	0.0	4.0
Deep fluid chemistry	36	1.0	2.0	2.0	3.0	3.0	0.0	0.0	0.0	2.0
2D surface seismic	31	2.0	2.0	2.0	2.0	2.0	0.0	0.0	0.0	1.0
Atmospheric gas concentration	31	0.0	0.0	0.0	0.0	0.0	4.0	3.0	0.0	4.0
Soil gas concentrations	25	0.0	0.0	0.0	0.0	0.0	4.0	1.0	0.0	4.0

Figure 2-10. Snapshot of recommendations for IEAGHG monitoring tool package to be implemented in an aquifer during the CO_2 injection phase for the selected monitoring objectives. The monitoring tools in Red are ones identified to have been assigned the highest scores across the selected aims and are strongly recommended techniques (Score 4).



Scenario name	Enter scenario name here ... [2019-06-24 16:51:47]
Location	Onshore
Depth	1500 to 2500 m
Type	Oil
Quantity	200.000 Mt (10.000 Mt/yr for 20.0 yrs)
Package	Agricultural+Syn-injection+Core

Tool	Rating %	Plume	Top-Seal	Overburden	Detect	Quantify	Wellbores
3D surface seismic	62	4.0	3.0	4.0	1.0	0.0	3.0
Atmospheric gas concentration	46	0.0	0.0	0.0	4.0	3.0	4.0
Soil gas concentrations	38	0.0	0.0	0.0	4.0	1.0	4.0
Surface-atmospheric gas flux	38	0.0	0.0	0.0	3.0	3.0	3.0
Geophysical logs	38	1.0	2.0	2.0	0.0	0.0	4.0
Downhole pressure/temperature	38	1.0	4.0	1.0	0.0	0.0	3.0
Deep fluid chemistry	29	1.0	2.0	2.0	0.0	0.0	2.0
2D surface seismic	29	2.0	2.0	2.0	0.0	0.0	1.0
Airborne spectral imaging	25	0.0	0.0	0.0	3.0	0.0	3.0

Figure 2-11. Snapshot of recommendations for IEAGHG monitoring tool package to be implemented in an oil field during the CO_2 injection phase for the selected monitoring aims. The monitoring tools in Red are ones identified to have been assigned the highest scores across the selected aims and are strongly recommended techniques (Score 4).

3.0 Technology Readiness Level Assessment

This section summarizes the TRL criteria and status of CO_2 monitoring and modelling technologies. The assessment is aimed at describing the TRL of the technologies in relation to their ability to support industrial scale CO_2 storage projects.

3.1 TRL criteria for CO_2 storage monitoring technologies

TRL is a systematic metric to enable a consistent evaluation and discussion of the technical maturity of any given type of technology of interest along its respective innovation chain. The proven original technology readiness assessment model pioneered by NASA in the 1980s and guidance developed by the US Department of Defense in 2003 (DOD, 2005) was adapted by DOE Office of Environmental Management in 2008 as a means of assessing technology maturity in its major programs (Figure 3-1). The original model assists in identifying those elements and processes of technology development required to ensure that a given project satisfies its intended purpose in a safe and cost-effective manner that will reduce life cycle costs and produce results that are defensible to expert reviewers.

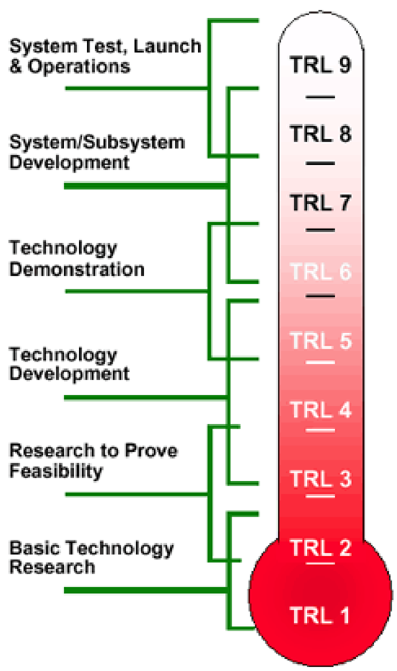


Figure 3-1 NASA Technology Readiness Levels.

(Picture Credit: By NASA/Airspace Systems (AS) - http://as.nasa.gov/aboutus/trl-introduction.html at the Wayback Machine (archived on 6 Dec 2005), Public Domain, https://commons.wikimedia.org/w/index.php?curid=65946549)

While the TRL scale can generally assess how far a given technology development has proceeded, in order to capture the inherently different system functions and operational considerations that are part of the Clean Coal Research Program, the Office of Fossil Energy in the US DOE came up with two sets of TRL definitions for the power generation systems and carbon storage systems in 2012. Figure 3-2 shows these CO_2 storage technology TRL definitions and descriptions that were applied in the updated 2014 Technology Readiness Assessment guidance issued by the DOE-NETL. The TRL scale ranges from 1 (basic principles observed and reported) through 9 (actual system operated over the full range of expected conditions). The TRL scores required that the technology be tested in a proper environment over the appropriate operational range of environmental variables and fidelity requirements. Progressively higher technical and financial risks are required to achieve the TRLs up to and including TRL-9.

Usage of TRL in the European Union, in all its major programs, was implemented in 2014 subsequent to the European Commission Decision in its framework program for driving and funding research and innovation called Horizon 2020. Figure 3-3 shows the list of TRL definitions in the Horizon 2020 Work Programme reports. This is a comparable scale based on the NASA definitions, with 9 TRLs ranging from 1 (basic principles observed) through 9 (actual system proven in operational environment).

Office of Fossil Energy | National Energy Technology Laboratory

TECHNOLOGY READINESS ASSESSMENT

Table 2. **DOE-FE CO_2 Storage Technology TRL Definitions and Descriptions**

TRL	DOE-FE Definition	DOE-FE Description for CO_2 Storage
1	Basic principles observed and reported	Lowest level of technology readiness. Scientific research begins to be translated into applied R&D. Examples include paper studies of a technology's basic properties.
2	Technology concept and/or application formulated	Invention begins. Once basic principles are observed, practical applications can be invented. Applications are speculative, and there may be no proof or detailed analysis to support the assumptions. Examples include analytic and laboratory studies to confirm the potential practical application of basic processes and methods to geologic storage.
3	Analytical and experimental critical function and/or characteristic proof of concept	Active R&D is initiated. This includes analytical studies and laboratory-scale studies to physically validate the analytical predictions of separate elements of the technology. Examples include components that are not yet integrated or representative. Components may be tested with simulants.
4	Component and/or system validation in a laboratory environment	The basic technological components are integrated to establish that the pieces will work together. This is relatively "low fidelity" compared with the eventual system. Examples include integration of "ad hoc" hardware in a laboratory and testing with a range of simulants.
5	Laboratory-scale similar-system validation in a relevant environment	Laboratory validation of system/subsystem components. Laboratory validation testing of geologic storage processes, subsystems and/or subsystem components under conditions representative of in situ operation. Subsystem and/or component configuration is similar to (or matches) the final application in almost all respects. Validation testing involves measurements under in situ operating conditions to assess performance of the process, subsystem and/or component. Planning and design are undertaken for prototype system verification.
6	Engineering/pilot-scale, prototypical system demonstrated in a relevant environment	Prototype system verified. Prototype field pilot testing of geologic storage system or subsystem in relevant geologic environments. Geologic characteristics, including rock type and contained fluids, depth, pressure, and temperature are relevant to final scale. Pilot scale involves injection of a sufficient amount of CO_2 to verify design performance of system or subsystem and components. System configured to enable pilot-scale testing, which involves measurements and operations specific to assessing performance of the system and/or subsystem and subsystem components. Performance testing relevant to the lifecycle of a storage project, including site characterization, injection, and post-injection monitoring and closure.
7	System prototype demonstrated in a plant environment	Integrated pilot system demonstrated. Geologic storage system prototype tested at pilot scale for a type of depositional environment (e.g., saline fluvial deltaic) or storage type (e.g., EOR or enhanced coalbed methane [ECBM]). Pilot scale involves injection of a few hundred tonnes[‡] to several hundred thousand tonnes. System configured to enable pilot-scale testing, which involves measurements and operations specific to assessing performance of the system, subsystem, and subsystem components. Performance testing is relevant to each stage of the full lifecycle of a storage project, including site characterization, injection, and post-injection monitoring and closure. Planning and design are undertaken to test and demonstrate a full-scale system.
8	Actual system completed and qualified through test and demonstration in a plant environment	System tested and demonstrated at final scale. This TRL represents the end of technology development for a geologic storage system for a type of depositional environment (e.g., saline fluvial deltaic) or storage type (e.g., EOR or ECBM). The complete geologic storage system is tested at final scale in a demonstration. Final scale involves injection of >1 million tonnes per year. System configured to enable final-scale testing, which involves measurements and operations specific to assessing performance of the system, subsystem, and subsystem components. Performance testing is relevant to each stage of the full lifecycle of a storage project, including site characterization, injection, and post-injection monitoring and closure.
9	Actual system operated over the full range of expected conditions	System proven and ready for final-scale geologic storage. Geologic storage system is proven through successful operations at full scale for a type of depositional environment (e.g., saline fluvial deltaic) or storage type (e.g., EOR or ECBM). Full scale involves injection of >1 million tonnes per year. System configured for final-scale deployment, including considerations of cost. Operations include full lifecycle of the storage project, including site characterization, injection, and post-injection monitoring and closure.

Figure 3-2. CO_2 storage technology TRL definitions and descriptions that were applied in the updated 2014 Technology Readiness Assessment guidance issued by the DOE-NETL (Table 2 in DOE/NETL – 2015/1711)

European Commission Technology Readiness Levels

- TRL 1 – basic principles observed
- TRL 2 – technology concept formulated
- TRL 3 – experimental proof of concept
- TRL 4 – technology validated in lab
- TRL 5 – technology validated in relevant environment (industrially relevant environment in the case of key enabling technologies)
- TRL 6 – technology demonstrated in relevant environment (industrially relevant environment in the case of key enabling technologies)
- TRL 7 – system prototype demonstration in operational environment
- TRL 8 – system complete and qualified
- TRL 9 – actual system proven in operational environment (competitive manufacturing in the case of key enabling technologies; or in space)

Figure 3-3. Snapshot of TRL definitions listed in Annex G of the General Annexes to the Work Programme 2016/2017 (http://ec.europa.eu/research/participants/data/ref/h2020/other/wp/2016-2017/annexes/h2020-wp1617-annex-ga_en.pdf).

3.2 TRL evaluation of monitoring technologies

Monitoring, Verification and Accounting or MVA is an important and specific aspect of the CCS program. CO_2 storage monitoring technologies can often only be truly validated in the subsurface, so technical staff have difficulty rating methods with conventional TRLs due to overlapping considerations. Table 3-1 summarizes the TRLs for CO_2 storage monitoring applications adopted for this study. The CCS specific TRL system adapted for CO_2 storage monitoring technologies is defined below.

1. ***Basic technology research***- This is the lowest level of technology readiness. For evaluation of CO_2 monitoring technologies, this level features scientific research on the feasibility and applicability of existing monitoring technologies with CO_2 substituted and related risk assessments. For new technology applications, this TRL would include paper studies to generate new research ideas and hypotheses to address scientific issues or gaps identified in existing technologies. This TRL maps to US-DOE TRL level 1 and European TRL levels 1 and 2.
2. ***Research to prove feasibility***- This next stage in technology readiness is where the proof of concept and practical applications begin to be invented. This TRL represents analytic and laboratory studies to demonstrate and verify the application of CO_2 monitoring technologies in their intended geologic environment(s). Proof of concept studies are expected to validate the hypotheses identified for new technologies in TRL 1 that would be followed by active R&D for screening and evaluation of critical elements needed for practical application and envisioned tool deployment. This TRL maps to US-DOE TRL level 2 and 3 and European TRL level 3.

3. ***Technology development-*** The system with its integrated components is validated to test their performance under conditions representative of their intended operating and geologic conditions. A key milestone expectation in TRL 3 would be to demonstrate the safety, sensitivity and specificity of the monitoring tool as a result of the extensive laboratory-scale validation. This would ensure that the tool fulfills its intended purpose by not posing any operational hazards while limiting conditions to "sense" or monitor the parameter of interest and the conditions triggering false positives are identified. This TRL maps to US-DOE TRL levels 4 and 5 and European TRL level 4.
4. ***Technology prototyping-*** Field pilot testing of the monitoring tool prototype is conducted in intended or relevant environments to demonstrate and optimize its operation and measurement efficacy. This TRL also includes performance testing of the final design to demonstrate safe, reliable and reproducible operation. QA/QC criteria are established for standard testing and implementation of the final design in alignment with industry regulatory and safety requirements. This TRL maps to US-DOE TRL levels 5 and 6 and European TRL levels 5 and 6.
5. ***Technology demonstration-*** This TRL represents the end of technology development with the system configured to enable final large-scale testing of the monitoring technology in each relevant stage of the full lifecycle of the geologic CO_2 storage project within the expected range of operating conditions. Implementing the technologies in large-scale demonstration projects helps in the identification of dependencies of different performance metric efficacies under the expected range of operational conditions. This TRL maps to US-DOE TRL levels 7 and 8 and European TRL levels 7 and 8.
6. ***Technology commercialization-*** The monitoring technology is proven ready for commercial applications at this highest TRL through repeated successful operations at full-scale for the intended geologic and operational environments. This TRL level includes technical as well as cost considerations for commercial-scale or industrial-scale deployment through the lifecycle of the geologic CO_2 storage project. This TRL maps to US-DOE TRL levels 8 and 9 and European TRL level 9.

Technologies that are considered fundamental and more established in CCS operations like operational monitoring, wireline deployed well logging tools, downhole pressure/temperature monitoring, and well integrity related monitoring show higher ratings. Most of the CCS monitoring technologies such as seismic monitoring, operational pressure and temperature monitoring, fluid sampling are TRLs 5 or 6 already as they have been borrowed from existing oil and gas experiences. Emerging, lower TRL technologies between TRL levels 2 through 4 include novel tracers such as experiments at Otway with noble gas tracers for direct measurements of residual trapping and laser tomography with the automated GreenLITE (Greenhouse gas Laser Imaging Tomography Experiment) system tested at the ZERT field site and Illinois Basin-Decatur Project site to detect and visualize real-time changes in atmospheric CO_2 concentrations. Higher TRL, and hence more established, technologies would be preferable for implementation in large-scale commercial projects while research projects would tend to include the deployment and performance evaluation of emerging technologies as part of their typically comprehensive monitoring and verification plan.

Table 3-1. CCS Technology Readiness Level Definitions and Descriptions.

TRL Level	**1**	**2**	**3**	**4**	**5**	**6**
Definition	Basic Technology Research	Research to Prove Feasibility	Technology Development	Technology Protoyping	Technology Demonstration	Technology Commercialization
Basic description	Basic principles formulated.	Application of principles and characteristic proof of concept of technology	Laboratory-scale validation in relevant environments to identify preliminary product.	Pilot-scale validation in relevant environments to optimize and demonstrate product operation and efficacy.	Large-scale/ full-scale demonstration in relevant environments.	Operational under full range of expected conditions.
Activities	Scientific "paper studies" to generate research ideas, hypotheses, and experimental designs for addressing the related scientific issues.	Active research and development to observe and validate the basic principles and hypotheses. Identify, screen and evaluate critical elements needed for practical application.	Identify, screen and evaluate components and critical design features needed by exploring prototypes. Utilise user feedback and testing to iterate and eliminate design choices.	Test representative engineering scale prototype in relevant environment to demonstrate readiness. Testing to cover realistic ranges of expected environmental conditions the technology is intended to be used for. Establish QA/ QC criteria.	Demonstrate implementation of full-scale system in its final form and expected conditions.	Actual operation of the technology in its final form under the full established range of operating conditions.
Expected Milestones	Initial intellectual property search for patentability.	Demonstrate proof of concept. Demonstrate preliminary validation of separate elements of technology in achieving intended design objectives.	Demonstrate preliminary efficacy of components and the integrated system in achieving intended design objectives. Demonstrate safety, sensitivity and specificity with trial matrices.	Demonstrate reliable, reproducible performance of technology aligned with industry regulatory and safety requirements (as needed).	Validate and finalize QA/QC criteria. Identify dependencies of performance metric efficacies under the expected range of operational conditions for the scaled-up technology.	Post-implementation surveilance for potential design improvements.
US-DOE TRL Mapping	1	2,3	4,5	5,6	7,8	8,9
European TRL Mapping	1,2	3	4	5,6	7,8	9
CO_2 Monitoring Technology Applications in CCS Project Lifecycle	CO_2 resource studies, substitution analysis for CO_2 with existing technologies, monitoring best practices reviews, FEPs type risk analysis, basinal geology assessments	Lab studies to verify CO_2 monitoring technologies, CO_2 resource modelling, site screening and feasiblity studies	Lab studies to demonstrate safe operation of all integrated components of monitoring technologies in intended range of subsurface conditions	Field testing of CO_2 monitoring technologies at small scale pilot tests, baseline monitoring, planned release tests	Application of monitoring technologies for full life cycle, large areas, real-life regulations	Industrial scale, integrated with CCS
CCS Projects	JOULLE, IPCC	Model intercomparison study, regional resource evaluations, economic analysis	Research studies	ZERT, DOE Phase II C-Partnerships, Frio-Experiment, STEMM	DOE Phase II projects, In Salah, Mountaineer	Quest, Sleipner, ADM, Aquistore

3.3 TRL Progress Review of CCS Projects

Given the TRL process, the study reviewed implementational aspects in current CCS projects to answer questions such as what level of monitoring technologies are currently being deployed at CO_2 storage sites? Are operators using technologies that are "ready for launch"? Do some sites still require additional technology development to address the unique risks presented by large-scale CO_2 injection? Are there enough cost-effective options available to address project risks? As described in Section 2.2, there was a great deal of pioneering research on monitoring CO_2 storage from approximately 1990-2010. This research provides guidance on the various methods available for CO_2 monitoring. There is experience and precedent for deploying the monitoring technologies. Major technology vendors have at least some degree of understanding of the requirements for CO_2 monitoring.

Since many CO_2 storage monitoring technologies were adopted from the oil & gas or environmental industries, the methods were already at TRLs of 4-5. The technologies only required validation and demonstration in CO_2 environments. Figure 3-4 illustrates general TRL ratings for CO_2 storage monitoring technologies. As shown, the technologies were generally in the 4-8 range (NOTE: this study was focused on readily available technologies).

However, most technologies for CO_2 storage still require some additional feasibility or screening studies to make sure they will be effective given site-specific conditions. For example, seismic survey methods like 4D surveys, vertical seismic surveys, and crosswell seismic can benefit from CO_2 substitution feasibility analysis to ensure CO_2 saturation would create a detectable change in sonic properties of the subsurface given the rock properties. Some persistent challenges remain for CO_2 storage projects:

- Monitoring wide areas in the subsurface or surface remains difficult. Automated processing of large data streams produced by distributed sensing systems also presents a challenge for many of the new technologies like DTS and DAS.
- Monitoring options that do not require construction of deep or intermediate zone monitoring wells may help to reduce costs for monitoring deployment.
- Ensuring the reliability of downhole devices for long periods of time (20-50 years) is also a challenge due to harsh downhole conditions.
- Options for monitoring wellbore integrity that does not interrupt operations is another technology need.
- Wellbore integrity monitoring for fields with hundreds to thousands of legacy oil & gas wells is a cost issue for CO_2-EOR and associated storage.
- The accuracy and repeatability of some geophysical methods is a concern where the results are subject to high processing and interpretation. These issues may lead to false positives/negatives, multiple versions of output, and subjective results.
- Monitoring CO_2 plume stability may be difficult in certain geologic settings where it may take a long period of time for the plume to completely stabilize, leading to drawn out monitoring.

As expressed in the interviews section of this report, most experts on CO_2 storage believe there is room to refine and improve CO_2 monitoring technologies. Given these issues, the TRL of CO_2 storage monitoring technologies appears to be suitable for supporting large-scale industrial CO_2 storage projects.

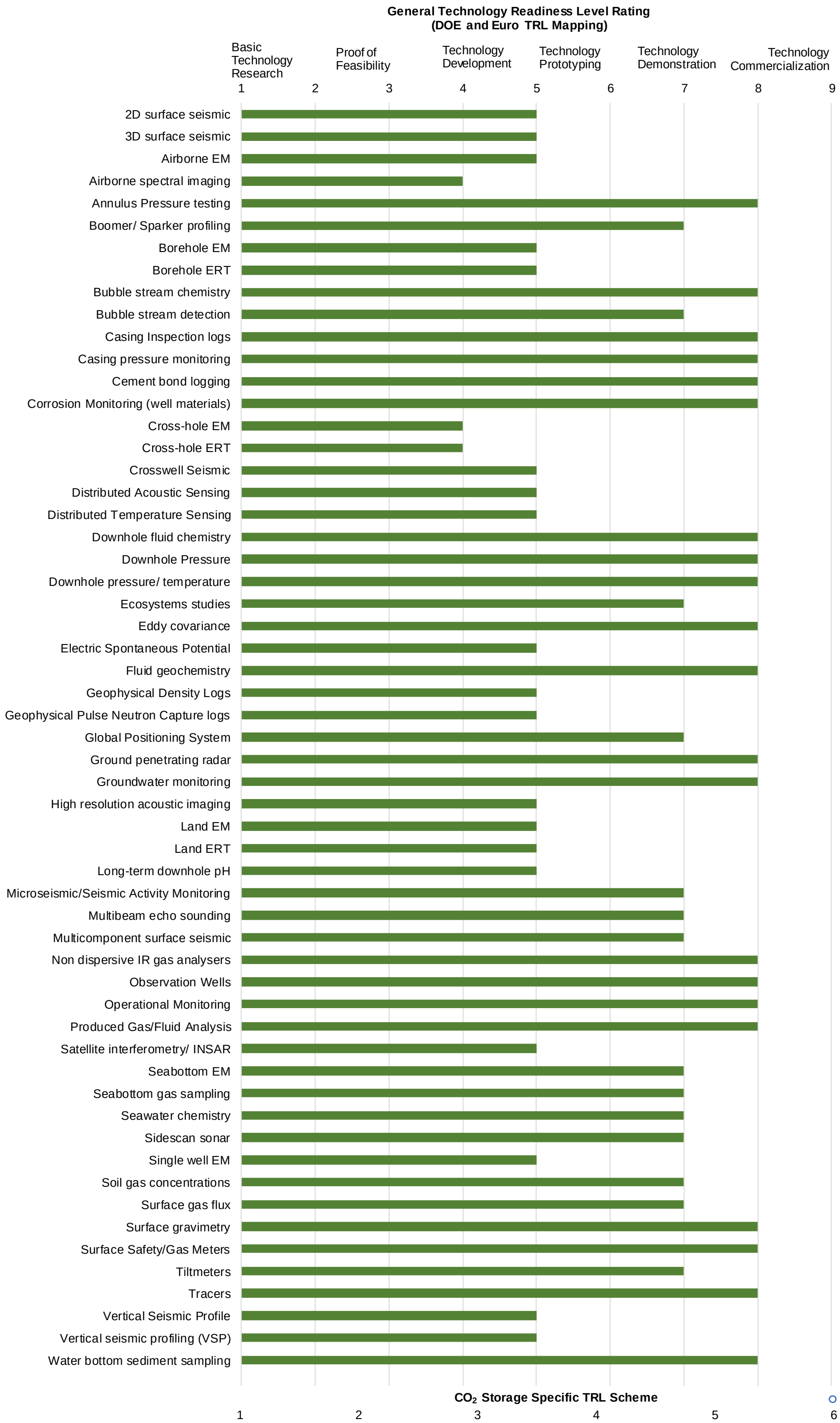


Figure 3-4. General Technology Readiness Level Ratings for CO_2 Storage Monitoring Technologies.

4.0 Large-scale CCS Projects for Case Studies

This section contains a description of several large-scale CCS projects monitoring and modelling programs. The description highlights the state-of-the-art monitoring methods and cost-benefit approaches taken to address project risks at field sites.

4.1 Survey of CCS projects status and CO_2 storage monitoring objectives

As of 2019, there were over 180 CCS projects listed in the Global Carbon Capture and Storage Institute (https://co2re.co/FacilityData) and US DOE CCS Database (https://www.netl.doe.gov/coal/carbon-storage/worldwide-ccs-database). The status of these projects ranges from planning stage projects to fully operational projects with more than ten years of operating history. Project scales range from effectively zero carbon captured and stored for projects that were canceled in the early development phases, to more than 10 Mt of CO_2 storage underground in active operational projects.

For this study, CCS projects with a longer history of injection at industrial scale (>1 Mt injection) were prioritized. Projects with longer monitoring histories and full life-cycle monitoring were also prioritized, because these projects illustrate the changes in monitoring programs as the operators adjust to project risks and monitoring data feedback. In addition, projects with the objective of testing monitoring technologies were also considered, because these projects present information on the deployment of multiple technologies. Finally, availability of cost information was also a factor in case study selection.

Several large-scale CCS projects were identified to illustrate the application of CO_2 storage monitoring technologies and cost-benefit progress. These projects have a wide range of site-specific risks, geologic settings, regulatory policies, and societal considerations. Interviews were completed with the key personnel from the case studies to get feedback on practical aspects of monitoring technologies, costs, and perspective on future developments for CO_2 storage programs. The case studies selected included the following projects:

1. Quest (Alberta, Canada) - integrated industrial CCS project, ~4 Mt
2. Sleipner (North Sea, Norway) - offshore CCS project with long-term monitoring, ~17 Mt
3. MRCSP Niagaran Reefs (Michigan, USA) - ~2.2 Mt,
4. In Salah (Algeria) & Mountaineer (WV, USA) - full life-cycle, integrated industrial scale projects,
5. Pilot and smaller scale projects (various locations), <1 Mt.

These projects illustrate the progression of CO_2 storage monitoring programs from more research-oriented projects to routine industrial scale operations.

4.2 Cost survey on case study projects' monitoring field applications

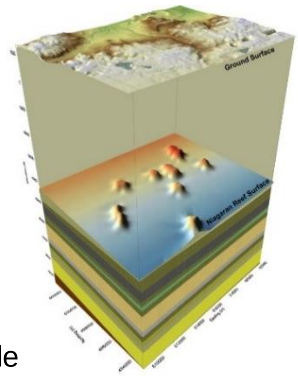
Cost surveys on case study projects' monitoring field applications are provided in the following pages. Project summaries were prepared to describe the overall project timeline, CO_2 source, injected CO_2 mass, geologic reservoir, regulatory policy drivers, and monitoring program. The various technologies deployed in the projects' monitoring programs were also described based on costs for deployment. The monitoring technology cost estimates were based on either project interviews, invoices from project activities, or technical articles. In general, the costs reflect vendor costs only, and do not necessarily include initial capital construction costs for items like deep wells, on-site support from the project site staff, and technical support for analysis of the monitoring data. These "hidden costs" are difficult to track consistently and may add a fair amount to monitoring costs. A basic cost-benefit number was estimated on a cost per tonne CO_2 stored and monitoring costs per year.

The project summaries illustrate several key themes regarding the cost-benefit potential for CO_2 storage:

- There is a large range in monitoring costs: from $10,000s for routine operational pressure and temperature monitoring to $1,000,000s for 4D seismic monitoring. Thus, it is difficult to interpret the cost-benefit ratio for these methods.
- Economies of scale are evident for monitoring programs. As projects inject greater volumes of CO_2 and streamline monitoring programs, costs on a tonne basis decrease.
- The frequency of monitoring events may be related to injection mass thresholds, calendar year, regulatory requirements, and capture system operations. There may be opportunity to reduce monitoring based on technical thresholds rather than routine intervals.
- It is difficult to separate capital costs of system construction, well drilling, site characterization, administrative support, and technical support.
- Research-oriented pilot-scale projects had fairly high costs to validate technology, but there is a clear opportunity to reduce monitoring costs as project move to routine injection operations.
- Some of the early projects were not subject to extensive regulations and had simpler monitoring programs with lower costs.
- Monitoring costs are a small fraction of the entire CCS project, especially when compared to capital and operating costs for CO_2 capture and compression where there may be little opportunity to reduce costs.
- Many of the monitoring methods have reasonable costs compared to the capital costs of drilling and constructing deep wells, pipelines, and compression facilities.

A description of the case study projects' monitoring programs and costs is presented in the following pages.

Midwest Regional Carbon Sequestration Partnership Niagaran Reef CO_2-EOR Industrial-scale Demonstration



Project Information

Location- Otsego County, Michigan, U.S.A.
CCS System- CO_2-EOR, research
Funding/Operator- U.S. DOE/Core Energy, Battelle

CO_2 Source- Natural gas processing facility
Regulations- U.S. EPA Underground Injection Control Class II (oil & gas related injection)

Geologic Setting- Michigan Basin, 1500-2000 m deep
Reservoir- Carbonate reefs, dolomite and carbonates
Caprock- anhydrite/salt layers
Total CO_2 Storage- 2,200,000 tonnes (1996-2018)
Major Risks- wellbore integrity, geomechanical effects, capacity

Monitoring Methods and Costs

Monitoring Technology	Costs*	Comments
BoreHole Gravity Survey	$75,000	1 well / 17 stations / 68 measurements
Microseismic	$489,000	21 day survey
Cross-well Seismic	$340,000	400 vertical feet / 10 foot receiver spacing
DTS	$460,000	6,800 feet (full length of well)
DAS VSP	$125,000	Two 65,000 lb Vibroseis trucks, 176 shotpts
VSP	$480,000	Multi-azimuth (8 lines), 4 days of acquisition
PNC	$168,000	1 baseline & 2 repeat surveys
INSAR	$303,000	80 km2, 29 ACR stations
Reservoir Geochemical Analysis	$143,000	9 wells over 5 yrs gen. geochem. & isotopes
Downhole Pressure Gauges	$86,775	9 gauges & calibrations
Wellhead Gauges	$30,050	2 gauges & calibrations
Total	$2,700,000	

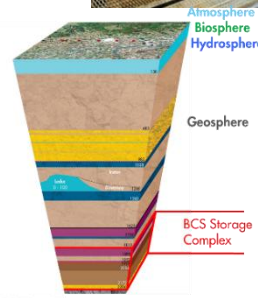
*costs based on invoices for monitoring services & materials. Costs do not include well installation, well construction, technical staff & administrative support. (Gupta et al., 2013; 2014; Kelly et al., 2014, Mawalkar et al., 2019)

Cost-Benefit Analysis

Total costs = $2,700,00 USD (2004-2017)

Monitoring costs per tonne = $1.23/ tonne*
Monitoring costs per year = $208,000/year (assuming 2004-2017 operation)*

Quest Carbon Capture and Storage Facility



Source: Rock & O'Brien, AAPG, 2016
https://www.equinor.com/en/what-we-do/new-energy-solutions.html

Project Information

Location- Alberta, Canada
CCS System- CO_2 storage, industrial
Funding/Operator- Shell

CO_2 Source- Oil sand refining upgrader
Regulations- Alberta CCS Statutes Amendment Act

Geologic Setting- Williston Sedimentary Basin
Reservoir- Basal Cambrian Sands, 2000 m deep
Caprock- Cambrian shale and siltstone
Total CO_2 Storage- ~4,000,000 tonnes (2015-2019)
Major Risks- public acceptance, injectivity, well integrity

Monitoring Methods*

Monitoring Environment	Monitoring Approach	Risk Assessment	Monitoring Stage		
			Baseline	Injection	Closure
Atmosphere	LightSource Laser CO_2 Mon.	CO_2 leakage rate to the atmosphere	✓	✓	✓
	Eddy Covariance Flux Mon.	CO_2 leakage rate to the atmosphere	✓	x	x
Biosphere	CO_2 Natural Tracer Mon.	Leak detection & impact	✓	(as needed)	(as needed)
	CO_2 Flux and Soil and Gas	CO_2 leak detection & impact assemnt	✓	(as needed)	(as needed)
	Remote Sensing (Brine & ND VI)	Leak detection & impact assessment	✓	x	x
Hydrosphere	Shell GW Wells:Cont. EC,pH	CO_2 leak detection & impact assemnt	✓	✓	✓
	Discrete Chemical and Isotropic Analysis on water and gas	Leak detection & impact assessment	✓	✓	✓
	Private Landowner GW Wells (discrete chemistry & Isotopes)	Leak detection & impact assessment	✓	✓	✓
Geosphere	Time-Lapse Walkaway VSP	2D distribution of CO_2 plume	✓	(as needed)	x
	Time-Lapse 3D Surface Seismic	3D distribution of CO_2 plume	✓	(as needed)	(as needed)
	INSAR	Pressure front & fault re-activation	✓	(as needed)	x
Deep Monitoring Wells	Downhole Pres. & Temp. above Storage Complex	Vertical distribution of pressure & temperature	✓	✓	✓
	Downhole MicroSeis. Mon.	Microseismic catalogue	✓	✓	x
Injection Wells	Injection Rate Metering	Rate and volume of CO_2 injected	✓	✓	x
	RST Logging	Leak detection & injection profile	✓	✓	x
	Temp. Logging	Leak detection outside casing	✓	✓	x
	Downhole Pres. & Temp.	Downhole pressure & temperature	✓	✓	✓
	Well Head Pres. & Temp	Injection pressure & temperature	✓	✓	✓
	Dist. Temp. & Acoustic Sensing	Leak detection outside casing	✓	✓	✓
	Annulus Pres. Mon.	Pressure leak detection	x	✓	✓
	Wellhead CO_2 Sensor	CO_2 leak detection	x	✓	✓
	Mechanical Well Integrity Testing	Leak Detection	x	✓	✓
	Operational Intergrity Assurance	Exception based well monitoring	x	✓	✓
	Cement Bond Logs	Initial quality of cement bond	✓	✓	✓
	Time-lapse ultrasonic casing imaging	Casing corrosion detection	✓	✓	✓

Cost-Benefit Analysis

Total Storage costs = $20,250,000 CAD*

*Monitoring Operational Costs** per tonne = $1.5-2.0 CAD/ tonne*

*Monitoring costs per year** = $1,500,000-$2,000,000 CAD/year*

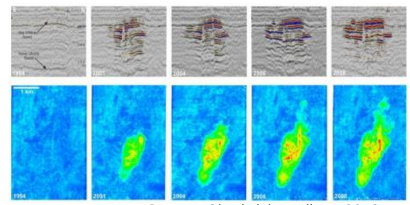
*costs estimated based on Quest project presentation (2017), including capital expenses.
**costs estimated based on interviews with project personnel.

Sleipner CCS Project

Project Information

Location- Offshore North Sea, Norway
CCS System- CO_2 storage, industrial
Funding/Operator- Equinor

CO_2 Source- Offshore natural gas processing platform
Regulations- Norwegian Petroleum Law



Source: Chadwick & Eiken, 2013

Geologic Setting- North Sea
Reservoir- Utsira Sand, 1000-2000 meters deep
Caprock- Nordland Group Shales
Total CO_2 Storage- ~17,000,000 tonnes (1996-2018)
Major Risks- CO_2 migration, seabed leakage, caprock leakage

Monitoring Methods and Costs

Monitoring Technology	Est. Costs*	Comments
4D Seismic	~ € 40,000,000[1,2]	10 surveys (including baseline)
Gravimetric surveys	(€ 300,000)	4 surveys
Controlled Source EM survey	NA	1 survey
Seabed surveys	(€ 300,000)	estimated
Chemical sampling of water column & seabed sediments	(€ 572,000)	estimated
Wellhead Gauges & Metering	(€ 60,100)	continuous
Total	~ € 42,000,000[1,2]	

*approximate costs estimated based on unit costs, research papers, not including technical staff & admin. support.

Cost-Benefit Analysis

Total costs = ~ € 42,000,000 (1996-2018)

Monitoring costs per tonne =~ € 2.00 / tonne*
Monitoring costs per year = ~ € 2,000,000 /year*

[1] Ringrose, P., Furre, A. K., Bakke, R., Dehghan Niri, R., Paasch, B., Mispel, J., ... & Hermansen, A. (2018, October). Developing Optimised and Cost-Effective Solutions for Monitoring CO_2 Injection from Subsea Wells. In 14th Greenhouse Gas Control Technologies Conference Melbourne (pp. 21-26).

[2]Chadwick, R.A.; Eiken, O.. 2013 Offshore CO_2 storage: Sleipner natural gas field beneath the North Sea. In: Gluyas, Jon; Mathias, Simon, (eds.) Geological Storage of Carbon Dioxide (CO_2): geoscience, technologies, environmental aspects and legal frameworks. Cambridge, UK, Woodhead Publishing, 227-253.

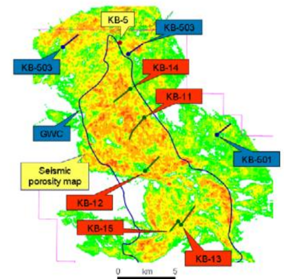
In Salah CCS Project

Project Information

Location- Krechba gas field, Central Algeria
CCS System- CO_2 storage, industrial
Funding/Operator- Joint Venture

CO_2 Source- Natural gas processing
Regulations- EU CCS Directive on
Geological Storage of Carbon Dioxide (Directive 2009/31/EC)

Geologic Setting- Krechba Gas field anticline
Reservoir- Carboniferous Sandstone, 1850-1950 meters deep
Caprock- Carboniferous mudstones, Cretaceous anhydrite
Total CO_2 Storage- ~3,800,000 tonnes (2006-2011)
Major Risks- wellbore integrity, caprock integrity, injectivity,
Geomechanical deformation



Source: Mathieson et al., 2011

Monitoring Methods and Costs*

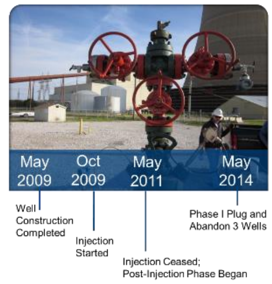
Monitoring Technology	Pre-injection	Operations	Post-injection/ Site Closure
4D seismic	X (1997)	X (2009)	NA
Microseismic		X	NA
Down-hole logging	X	X	NA
Well head space	X	X	NA
Shallow aquifer	X	X	NA
InSAR/Satellite imagery	X	X	NA
Tiltmeters		X	NA
Well Pressure	X	X	NA
Microbiology		X	NA
Surface Flux/Soil gas	X	X	NA
Tracers	X	X	NA
Wellhead Fluid		X	NA

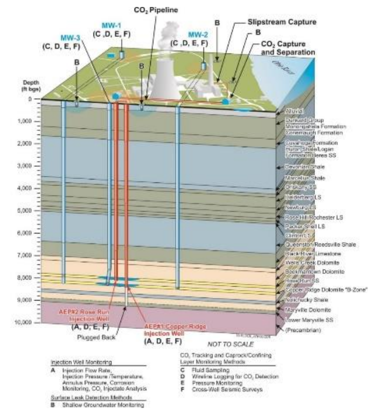
Cost-Benefit Analysis

Not Available

*after Mathieson, A., Midgelya, J., Wright, I., Saoula, N., and Ringose, P., 2011.In Salah CO_2 Storage JIP: CO_2 sequestration monitoring and verification technologies applied at Krechba, Algeria. Energy Procedia 4 (2011), 2596-3603.

Mountaineer Product Validation Facility CCS Project





Project Information

Location- West Virginia, USA
CCS System- CO_2 Storage, Industrial
Funding/Operator- AEP/Battelle

CO_2 Source- Coal Fired Power Plant
Regulations- West Virginia EPA
Underground Injection Control Class V

Geologic Setting- Appalachian Basin, 2300-2600 m deep
Reservoir- Rose Run Sandstone and Copper Ridge Dolomite
Caprock- Well Creek Shale & Black River Limestone
Total CO_2 Storage- 37,400 tonnes (2009-2011), site closure 2017
Major Risks- injectivity, capacity, induced seismicity, geochemical

Monitoring Methods and Costs*

Monitoring Technology	Baseline	Operations	Post-Injection/ Site Closure
CO_2 Injection Stream	$23,700	$10,800	-
Injection Well Flow and P/T Monitoring	$221,500	$10,800	$21,600
Corrosion Monitoring	NA (inhouse)	NA (inhouse)	NA (inhouse)
Surface CO_2 Monitoring	NA (inhouse)	NA (inhouse)	NA (inhouse)
Shallow GW Monitoring	$6,108	$18,324	$36,648
External MIT	$5,000	$15,000	$30,000
Pressure Falloff	NA (inhouse)	NA (inhouse)	NA (inhouse)
Microseismic Monitoring	-	$621,000	-
Wireline Logging/PNC	$36,000	$216,000	$216,000
Deep Well Fluid Monitoring	$7,200	$21,600	$66,700
Cross-Well Seismic	$207,500	$320,000	-
Deep Well P/T Monitoring	$81,000	$18,000	$144,000
Total	$588,008	$1,251,524	$514,948

Cost-Benefit Analysis

Monitoring costs per tonne = $63.0/ tonne*

Monitoring costs per year = $294,320/year*

Post-Injection Site Closure Monitoring costs per year = $85,833/year

Monitoring Methods and Costs* (*costs estimated based on based project invoices and quotes, not including technical support, administrative costs)

4.3 Large-scale CCS project Case Study Interviews

To obtain feedback from industrial-scale CO_2 storage projects, interviews were completed with technical personnel and managers of CO_2 storage projects. The objective of the interviews was to survey CO_2 storage projects that implemented monitoring technologies in context of site-specific risks, cost constraints, life-cycle events, and benefits. The analysis was aimed at evaluating the impact of each technology and priorities for future developments based on technology readiness. The interviews were structured with the following questions:

- What was the biggest risk concern for your site?
- What key monitoring technologies did you use at the site?
- How much did monitoring factor into total project efforts and costs?
- Which monitoring technologies were most effective? What was the most effective monitoring technology for plume tracking?
- What monitoring would you avoid if you had to do it again?
- Did you complete a cost-benefit analysis for the project? How did that compare with the initial expectations for key monitoring technologies at your site?
- How did your project's considerations evolve over time?
- What were relative costs for baseline pre-injection, injection operations, and post-injection monitoring phases of the project?
- Where do you see CO_2 storage monitoring programs headed in the next 10-20 years as more industrial-scale CCS projects are implemented?

The projects selected for interviews were focused on industrial-scale CO_2 storage at the scale of 1 Mt CO_2 injection. However, most of the projects involved some degree of research. These projects provide a review of the status of the potential for improving the cost-benefit ratio of reducing risk for CO_2 storage projects. Interviews were completed with personnel with experience on the following projects:

- Quest CCS Project (Alberta, Canada) - integrated industrial CCS project @ 1 Mt/yr,
- Midwest Regional Carbon Sequestration Partnership Niagaran Reefs (Michigan, USA) - multiple monitoring tech. applications, CO_2-EOR and "45Q" mmv programs, 2.2 Mt storage total,
- ADM Decatur CCS Project (Illinois, USA) - integrated industrial CCS project @ 1.1 Mt/yr,
- Weyburn CO_2 Monitoring and Storage Project (Saskatchewan, Canada)- integrated CCS CO_2-EOR @ 2.3 Mt/yr,
- Aquistore/Boundary Dam (Saskatchewan, Canada) - integrated industrial CCS project @ 140 t/yr,
- In Salah CCS Project (Central Algeria) - integrated industrial CCS Project @ 3.8 Mt total,
- Mountaineer CCS Product Validation Facility (West Virginia, USA)- integrated CCS pilot scale test @ 37,000 t total,
- Sleipner CCS Project (North Sea, Norway) - integrated industrial offshore CCS project @ 1 Mt CO_2/year,
- Petra-Nova (Texas, USA) - integrated industrial CCS project, CO_2-EOR @ 1.6 Mt per year,
- Nagaoka CCS Pilot-Scale Test Site (Niigata, Japan) - pilot scale CO_2 test @ 10,400 t CO_2.

The interviews were informal conversations that do not necessarily reflect the views or opinions of the companies operating these projects. The interviews were aimed at soliciting viewpoints based on site-specific experience balancing costs and monitoring technology applications. Key messages from the interviews with industrial scale projects are summarised as follows:

Status of CO_2 monitoring technologies

- There is confidence in the array of monitoring technologies available for CO_2 storage projects. There is also room for technology refinement and improvement. However, the path forward for implementing safe CO_2 storage projects appears stable.
- Current projects are benefiting from the research completed on pilot-scale and demonstration level CO_2 storage projects.
- All projects consider subsurface pressure and temperature as the most valuable monitoring method. Distributed pressure/temperature sensors and automated systems have provided useful options for monitoring subsurface pressure.
- Site characterization and baseline near-surface and atmospheric monitoring is critical to addressing stakeholder risks. These items may be scaled back during operations, but many projects have had incidents where the baseline monitoring was essential to addressing technical issues and erroneous stakeholder challenges to project operations.

CO_2 Storage Risks

- Stakeholder acceptance is the primary risk for most CO_2 storage project managers; therefore, there is value in performing stakeholder related near-surface and atmospheric monitoring near wellheads.
- All projects indicated that shallow groundwater and baseline soil gas or atmospheric monitoring was high risk priority for public acceptance, but then all projects indicated that this monitoring would be scaled back during operations after the baseline was determined.
- A wide array of technical risks are present at CO_2 storage sites, and each project had different risk concerns to address with their monitoring programs, mostly related to geological features of the subsurface system.
- Wellbore integrity was a key risk for any site with legacy oil and gas wells.

CO_2 Storage Monitoring Cost-Benefit

- Specific thresholds are necessary to help control monitoring costs, especially for delineating the CO_2 plumes and pressure fronts in terms of CO_2 saturation levels and pressure changes. Otherwise, costs may escalate trying to confirm vague terms like "CO_2 plume boundary" and "pressure front."
- Some technical project managers question the cost-benefit of monitoring the CO_2 plume within the reservoir since it can be very costly to delineate with any confidence. As long as the CO_2 is retained within the storage zone, the storage is effective.
- Some of the newer monitoring technologies output more data than is necessary for commercial CO_2 storage operations. Traditional monitoring methods may suffice for many projects and provide cost-benefit for the operator.
- Some geophysical methods that require a large amount of processing and interpretation are frustrating to project managers, because the methods provide unclear results. Some of these methods are also difficult to repeat because surface and/or subsurface conditions change. Costs can also escalate after field acquisition due to ongoing processing and interpretation.
- Cost-benefit analysis may be integrated into site characterization, risk analysis, modelling, monitoring program development, and system design.
- The value of cost-benefit analysis is not entirely clear to project managers and technical staff working on implementing CO_2 storage monitoring programs given the logistical challenges of deploying CO_2 monitoring technologies. A more standardized cost-benefit methodology may help with developing CCS projects.
- Research oriented projects were not especially constrained by costs, because the project objectives were often to field-test, verify, and improve monitoring technologies. Therefore, costs

for many of the early CCS are misleading. However, current industrial-scale projects have greatly benefited from the foundational research completed under the pilot-scale and demonstration projects.

- Commercial, industrial-scale CO_2 storage projects on the order of 1 Mt CO_2/year appear to have converged on monitoring costs of $1-4 million USD per year.
- CO_2 storage monitoring costs are a small fraction (<5%) of most CCS projects overall budgets, especially in comparison to capital and operating costs for carbon capture. However, some projects with lower capture costs (like ethanol plants and gas processing) may have higher relative monitoring costs, because the capture costs are low.
- "Hidden costs" related to capital expenses like well construction, site characterization, technical support, and administrative costs are often difficult to depict in cost analysis.

CO_2 Storage Plume Monitoring

- No single technology can track the CO_2 plume in the subsurface. Therefore, an array of monitoring methods is necessary.
- Many projects have shifted into a mode of confirming the monitoring/modelling predictions rather than exhaustive delineation of the CO_2 in the subsurface. For example, some projects indicated that 3D seismic was a technology being scaled back due to costs. This presents opportunity to reduce costs in a meaningful way.
- There are mixed views on some of the geophysical methods used for delineating CO_2 in the deep subsurface, mostly related to geological settings. Some of the geological settings make geophysical methods a challenge, with difficult to interpret results and low accuracy.
- Some sites have moved to a threshold and forward modelling approach to design monitoring programs. These approaches consider the material impact of CO_2 migration in relation to the monitoring technology.

CO_2 Storage Monitoring Program Operations

- Flexibility is needed in monitoring plans to focus on the more meaningful technologies, address unexpected results, and adjust monitoring over time to manage operational costs.
- Several projects noted that microseismic monitoring was intended to demonstrate caprock integrity but ended up being more of a stakeholder safety method to ensure there was no induced seismic activity related to CO_2 injection. Most projects thought that some degree of seismic monitoring would be required at all CO_2 storage projects.
- Some geologic settings will present challenges to monitoring. CO_2 plume stability will be difficult to establish in highly dipping formations with high permeability reservoirs.
- Regulatory compliance and environmental stewardship are drivers for high-level leadership at companies that are responsible for completing CCS projects.
- CO_2 storage project monitoring programs cannot not be standardized, but there are several central monitoring technologies that will be necessary at all sites like subsurface pressure, shallow groundwater, well integrity, and caprock/intermediate zone monitoring.
- There is value in systematic and process driven approaches to CO_2 monitoring. Tiered cost-benefit approaches can aid in managing project risk, costs, regulatory requirements, and field operations.

4.4 Life cycle cost analysis for monitoring technologies

Life cycle monitoring for carbon storage projects may include baseline, operational, and post-injection site closure monitoring. To be effective, carbon storage projects require effective storage for thousands of years. However, post-injection monitoring may be difficult to sustain in terms of financial support and attention when carbon capture and injection operations cease. Many CO_2 storage projects have intensive baseline monitoring, a regular operational monitoring schedule, and a decreasing amount of post-injection monitoring. These activities are often integrated into a routine risk assessment. Ultimately, the projects rely on the natural subsurface system to contain the CO_2, which is the fundamental concept of carbon storage. Monitoring information is key to verifying that the CO_2 is secure and safely underground with little risk to human health or the environment. The risk profile presented by Benson in the 2005 IPCC report (Metz et al., 2005) has prompted a fair amount of discussion on life cycle risks for CO_2 storage. It is not possible to monitor the CO_2 forever, and eventually the injected CO_2 will be similar to natural CO_2 fields.

Currently, there are few examples of industrial carbon storage projects that have completed a full life cycle into site closure. Many carbon storage projects are in the planning, baseline monitoring, or operations phase. Other projects were small scale pilots or CO_2-EOR applications that did not require much site closure monitoring. Two industrial projects that have completed the full baseline to site closure life cycle are the In Salah CO_2 Storage Project and the Mountaineer Integrated CCS Product Validation Facility. In addition, there are some analogs like natural CO_2 fields, offshore oil & gas operations, and natural gas storage that provide some examples of the type long-term or post operations monitoring necessary for gas storage in the deep subsurface.

In Salah CCS Project - The In Salah CCS project was completed from 2004-2011 in central Algeria. The CCS project injected 3.8 Mt CO_2 from a natural gas processing plant into a 1900 m deep sandstone formation with three horizontal injection wells. During injection, InSAR monitoring detected up to 20 mm of surface uplift, which was confirmed with modelling to be related to CO_2 injection. In addition, there was evidence from system monitoring of possible fracture flow into the caprock and some wellbore integrity issues. Thus, these items were identified in quantified risk assessments for the project. Table 4-1 summarizes the monitoring program at the In Salah CCS project. The project had two main injection periods June 2006-July 2007 and November 2009-March 2011, so some "baseline" monitoring occurred in between events after initial monitoring data was collected.

Table 4-1. Monitoring for In Salah CCS Project.

Monitoring Technology	Pre-injection	Operations	Post-injection/ Site Closure
4D seismic	X (1997)	X (2009)	NA
Microseismic		X	NA
Down-hole logging	X	X	NA
Well head space	X	X	NA
Shallow aquifer	X	X	NA
InSAR/Satellite imagery	X	X	NA
Tiltmeters		X	NA
Well Pressure	X	X	NA
Microbiology		X	NA
Surface Flux/Soil gas	X	X	NA
Tracers	X	X	NA
Wellhead Fluid		X	NA

Ringrose et al. (2013) note that the response to geomechanical deformation included increased modelling and InSAR monitoring. The response to wellbore integrity included a plug-and-abandon work on well KB-5, increased frequency of wellhead inspections, and evaluation of well-bore cement and CO_2 geochemical reactions. The In Salah CCS project was stopped for a combination of both geopolitical and scientific reasons, and there was not a great deal of post injection/site closure monitoring completed at the site. The project benefited from various monitoring technologies and integration into modelling. In this case, the project required increased monitoring during operations, and very little post-injection monitoring. The project may have lacked upfront well integrity surveys, microseismic monitoring, and geomechanical modelling. Costs were fairly low for baseline, moderate for operations, and low for post-injection/site closure. The project illustrates a potential life cycle for project subject to economic and geopolitical factors.

***Mountaineer Integrated CCS Product Validation Facility* -** The American Electric Power (AEP) integrated CCS Product Validation Facility was an integrated CCS project at an active coal fired power plant in Mason County, West Virginia, USA (Gupta et al., 2016). The project was a full lifecycle CCS project that began with site characterization in 2002, had active injection of 37,000 metric tons CO_2 from 2009-2011, and achieved U.S. Environmental Protection Agency site closure in 2017 (Figure 4-1). A performance-based risk analysis was used to identify potential risks and target design, operations, or monitoring efforts that would mitigate them (Battelle, 2009). The injection and monitoring system were designed to minimize risks, address surface issues at the active power plant site, maximize use of funds, and leverage lessons learned from other major projects around the world applied to site-specific conditions (Sminchak et al., 2006).

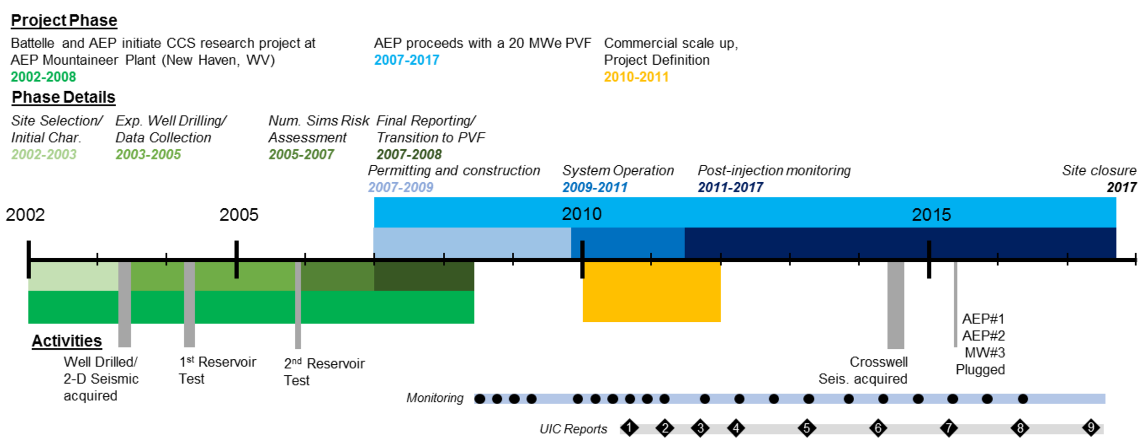


Figure 4-1. AEP Mountaineer CCS Product Validation Facility Project timeline.

Monitoring applied at the Mountaineer CCS site included injection system metering, shallow groundwater sampling, deep well fluid sampling, downhole wireline logging, downhole pressure, and cross-well seismic surveys (Battelle, 2009; McNeil et al., 2011). In addition, reservoir modelling was used to track the status of the CO_2 plume. Many of the monitoring requirements were dictated by the U.S. EPA Underground Injection Control regulations for Class V experimental wells. The project was implemented prior to UIC Class VI regulations, and the UIC requirements were influenced by local oil & gas operations.

After injection of 37,000 tonnes, the post injection and site closure monitoring involved groundwater monitoring, reservoir pressure monitoring, CO_2 plume modelling, and reporting to regulators. The UIC permit required that post-injection monitoring continue for twenty years unless it could be demonstrated that the CO_2 plume and pressure front stabilized and there was no danger to USDWs. Post-injection monitoring continued until the site closure was received in 2017, because monitoring showed that the CO_2

plume and pressure front were stable and that there was no further endangerment to the shallow aquifer groundwater resources.

Table 4-2 summarizes monitoring for the Mountaineer CCS project. As shown, there was a large amount of baseline and operational monitoring when some of the more expensive monitoring technologies were applied. The post-injection/site closure monitoring was less expensive, because the total amount of CO_2 injected was lower than planned. Post-injection monitoring was focused on ensuring pressures declined to normal, the CO_2 plume was stable, and the five deep wells had integrity. Some of the post-injection monitoring was integrated with the well plugging and abandonment activities, so costs were difficult to assess. No monitoring was completed after the wells were plugged. In general, the Mountaineer project represents a project at an active power plant influenced by regulations. Costs were moderate for baseline, high for operations, and low for post-injection/site closure, mostly because the site closed 15 years earlier than projected.

Table 4-2. Monitoring for Mountaineer CCS Project.

Monitoring Methods	Frequency	Baseline	Injection Operations	Post-Injection /Site Closure
CO_2 injection stream	Quarterly (during inj.)		X	
Injection well flow and P/T monitoring	Continuous (during inj.)		X	X
Corrosion monitoring	Quarterly		X	
Surface CO_2 monitoring	Continuous		X	
Soil gas tracer surveys	Annual	X	X	
Shallow groundwater sampling/analysis	Quarterly (during inj., semi-annual post-inj.)	X	X	X
External MIT	Annual	X	X	
Pressure fall-off testing	Every two years, after inj. start	X	X	
Microseismic monitoring	Continuous		X	
Wireline logging for CO_2 detection	Annual	X	X	X
Deep well fluid sampling and analysis	Annual	X	X	X
Cross-well seismic surveys	Annual	X	X	
Deep Wells P/T monitoring	Continuous	X	X	X
Costs (U.S. $)*		$588,000	$1,252,000	$543,000

*based on project invoices and quotes.

Analogs for CCS Life Cycle Monitoring - Analogs for CCS include natural CO_2 fields, natural gas storage, and offshore oil & gas. These analogs provide examples of long-term closure monitoring that may be required for CO_2 storage projects (Table 4-3). Large natural CO_2 fields are present in some sedimentary basins and near some volcanic sources (Allis et al., 2001; Stenhouse, 2003; Pearce et al., 2004). Most of these natural sources have minor CO_2 leakage and require limited monitoring (Nishi et al., 2000; Baines and Worden, 2004; Gouveia et al., 2004; Shipton et al., 2005; Annunziatellis et al., 2008; Beaubien et al., 2008). Offshore oil & gas operations provide examples of potential for leakage of gases into the seabed, especially in highly developed oil fields like the North Sea and Gulf of Mexico. Much of the monitoring in these areas is related to wellbore integrity (Bourgoyne et al., 2000; Vielstädte et al., 2019). Natural gas storage operations offer analogs for monitoring injected gases in the subsurface over long time periods. Much of the monitoring for natural gas storage is focused on wellbore integrity and atmospheric monitoring (Perry, 2005; US DOE & PHMSA, 2010).

Table 4-3. Summary of Monitoring Performed in CO_2 Storage Analogs.

Analog	Risk	Monitoring	Costs
Natural CO_2 fields	CO_2 migration, leakage	Thermistors, pressure transducers	Low
	Releases along faults, volcanos	Monitoring of seismic activity, gas flux measurements along surface fault zones	Low
Offshore Oil & Gas	Casing pressure, leaks	Flow testing, BHP, temperature surveys, fluid levels, seabed surveys, airborne	Medium
	Legacy wells, 'idle iron'	Field inspections, water quality monitoring, benthic studies, seabed surveys, aerial reconnaissance	Medium
Natural Gas storage	Well integrity	Well surveys, casing pressure surveys, cement bond logging,	Medium
	Gas migration	Field pressure surveys, ambient air monitoring, airborne methane surveys, gas sampling and composition analysis in other oil and gas wells, stored gas inventories	Low

4.5 Risk reduction categories

CO_2 storage monitoring technologies provide options to address site-specific risks which may impact project performance, storage security, human health, the environment, and surface features. Adherence to a risk assessment plan and ultimate public acceptance of a CO_2 storage program requires a detailed and customized monitoring, reporting, and verification (MRV) plan. Monitoring provides accountability for injected CO_2, meets regulatory requirements, provides leakage detection and assessment of CO_2 migration which are all key criteria in a risk assessment plan. An assessment of a storage site accounts for the capacity and containment of the CO_2, monitoring and regulation of injectivity, the potential migration paths of a CO_2 plume, the quantification of the plume migration, the demonstration and public acceptance of safe and effective storage (Figure 4-2).

Each site is specific and requires a tailored MRV program that focuses on atmospheric, surface/near-surface, and reservoir monitoring technologies to measure direct and indirect injection and migration of CO_2. Determination and understanding of monitoring technologies for a CO_2 storage program can be divided into three key parts: 1) understanding the key risk assessment criteria, 2) evaluation of the monitoring technologies available, and 3) a rating system to determine the final MRV program. A monitoring program should evaluate the capacity within the reservoir, the containment above the caprock, along the borehole and in the atmosphere, and the mitigation and contingency potential leakage of the CO_2. The following tables discuss the individual risk assessment criteria from Tables 4-4 through 4-9, the general summary of operational monitoring zones, and examples of the technologies used to meet the criteria needs.

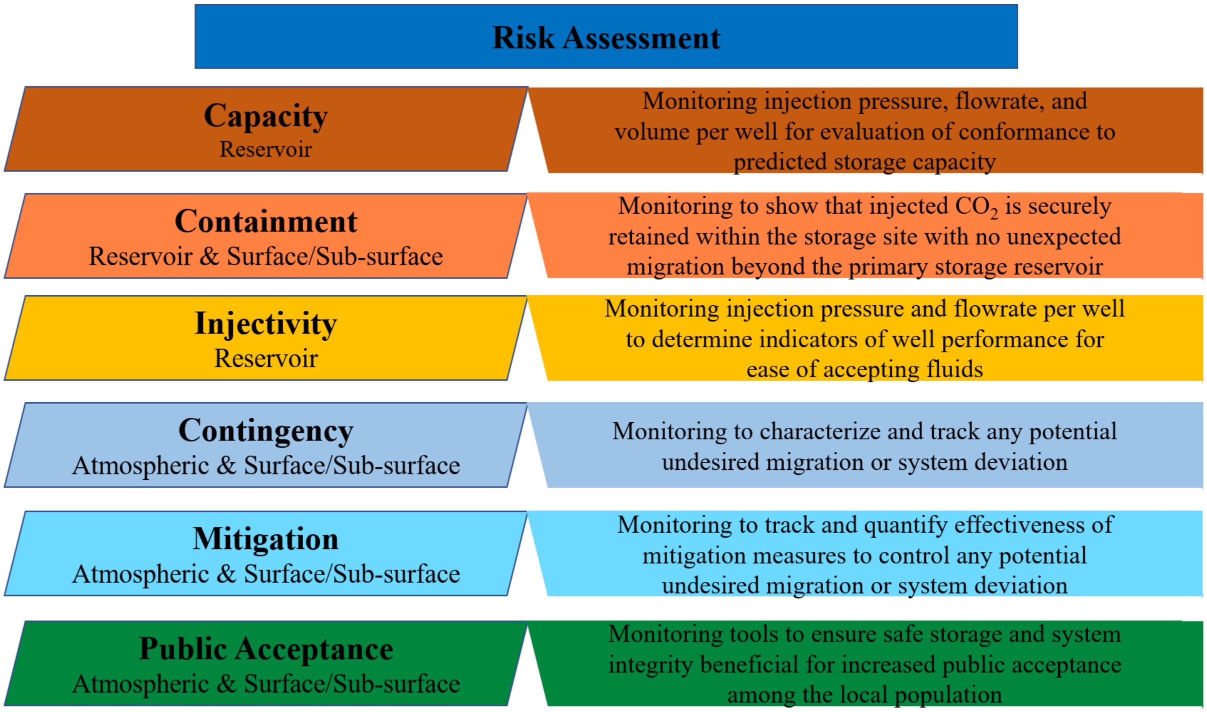
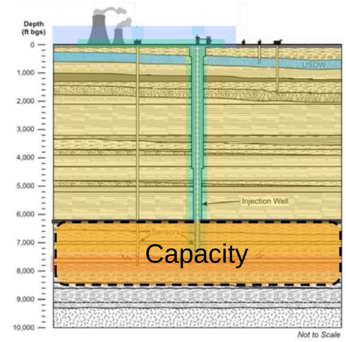


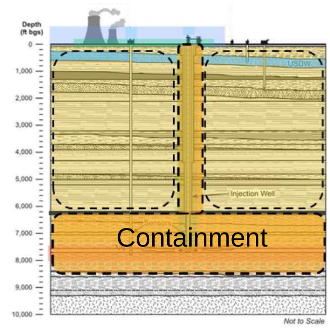
Figure 4-2. Risk assessment for monitoring programs involves considerations for six key risk categories that inform the selection of appropriate monitoring technologies.

Table 4-4. Risk assessment for capacity including risk monitoring zone and examples of technology.

Risk Monitoring	Atmospheric, A	Surface/ Near Surface, S/NS	Reservoir, R
1. Capacity			●
Definition: Monitoring injection pressure, flowrate, and volume per well for evaluation of conformance to predicted storage capacity. Capacity monitoring helps address risks to reduced confidence in the long-term effectiveness of CO_2 storage by determining if say, the observed pressure buildup in the storage complex does not agree with model-based predictions within the determined range of uncertainty. **Description:** Common monitoring technologies employed for capacity monitoring include seismic, downhole pressure gauges, and geophysical logging. Seismic is also used during the initial characterization of structural and spatial characterization of the target reservoir zone. It has a variety of limitations and is a large part of a MRV budget. Repeat seismic is used to determine structural changes and to potentially track the CO_2 plume migration. Geophysical logging identifies baseline lithology, density, and saturations the reservoir and caprock formations. For example, density tools combined with pulsed neutron capture tools measure the changes in lithology and the changes in porosity of the formations which can be used as inputs in models.	**Reservoir** 		

Example Technologies	Descriptions
2D Seismic	2D linear image for time-lapse monitoring to survey potential changes due to CO_2 injection
Geophysical Logs	Sensors or instruments designed to measure downhole rock properties, fluid/gas saturation, and downhole conditions as indicators of CO_2 saturation.
Pulsed Neutron Capture (PNC) Logs	Fluid saturation of cased wells, porosity indicator, can show porosity changes near wellbore which can be used to indicate potential wellbore integrity.

Table 4-5. Risk assessment for containment including risk monitoring zone and examples of technology.

<table>
<tr><th>Risk Monitoring</th><th>Atmospheric, A</th><th>Surface/ Near Surface, S/NS</th><th>Reservoir, R</th></tr>
<tr><td>2. Containment</td><td></td><td>●</td><td>●</td></tr>
<tr><td>Definition: Monitoring to show that injected CO_2 is securely retained within the storage site with no unexpected migration beyond the primary storage reservoir. Jenkins et al., 2015 define two elements of containment monitoring namely, deep-focussed surveillance and shallow-focussed monitoring.
Deep-focussed monitoring involves monitoring CO_2 within the target reservoir zone to identify unexpected migration of CO_2 out of the primary storage reservoir towards, ultimately the surface. Containment monitoring aims to address risks to storage security by detecting pressure migration within the defined area of review, migration of CO_2 within the target reservoir zone, potential CO_2 migration along well (injector, monitoring, legacy wells), along faults and matrix pathways, and any above-zone fluid migration to the lowest underground water zone, contamination of surface soils, and any release of CO_2 into the atmosphere.
Shallow-focussed monitoring technologies are more useful to monitor for containment in cases where there is a pre-determined high-risk specific potential pathway to the near-surface such as defective wellbores.
Description: Common containment monitoring technology includes seismic, geophysical logging, groundwater sampling, pressure gauges, and downhole fluid sampling: Groundwater monitoring, baseline and repeat sampling, provides chemical data to determine migrating CO_2. Baseline sampling should be conducted prior to CO_2 injection activities and is a commonly used to publicly demonstrate containment of the injected CO_2.
This technique is restricted to the shallow surface depths between 1.5m – 15+m (5ft – 50+ft). depending on bedrock formations. Groundwater testing is limited to the spread of wells and does not monitor deeper formations.</td><td colspan="3">Surface/Near-Surface/Reservoir
</td></tr>
</table>

Example Technologies	Descriptions
Downhole Fluid Chemistry	Formation fluids can be collected directly from the zone of interest
Groundwater Monitoring	Repeat sampling provides chemical data to determine migrating CO_2. into groundwater resources, high visibility monitoring, easy to communicate to stakeholders

Table 4-6. Risk assessment for injectivity including risk monitoring zone and examples of technology.

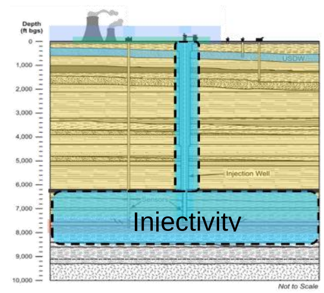
<table>
<tr><th colspan="2">Risk Monitoring</th><th>Atmospheric, A</th><th>Surface/ Near Surface, S/NS</th><th>Reservoir, R</th></tr>
<tr><td colspan="2">3. Injectivity</td><td></td><td></td><td>●</td></tr>
<tr><td colspan="2">Definition: Monitoring injection pressure and flowrate per well to determine indicators of well performance for ease of accepting fluids.
Injectivity monitoring aims to address risks to non-conformance of expected injectivity within the determined range of uncertainty. It can determine and measure possible near-well damage and salting out due to operations leading to reduced injectivity over time.
Description: Common injectivity monitoring technology includes downhole pressure gauges which is a common and effective method for monitoring changes in injectivity and production. Very few limitations are associated with this technology. Gauges are reliable and provide continuous in place monitoring. Longevity of this technology can be up to a year depending on battery and memory capacity. Limitations associated with pressure monitoring are limited: corrosion of gaskets can damage gauges and cause loss of data; measurements are only recorded at set depth of each gauge carrier and does not reflect the entire reservoir or monitored zone.</td><td colspan="3">Reservoir

</td></tr>
<tr><th>Example Technologies</th><th colspan="4">Descriptions</th></tr>
<tr><td>Downhole Pressure/Temperature</td><td colspan="4">Input to calculate and continuously track the injectivity index, gauge limitations include life of batteries (can potentially last up to a year)</td></tr>
<tr><td>Operational Monitoring</td><td colspan="4">Monitor injection performance for pressure increase and flow variations</td></tr>
</table>

Table 4-7. Risk assessment for contingency including risk monitoring zone and examples of technology

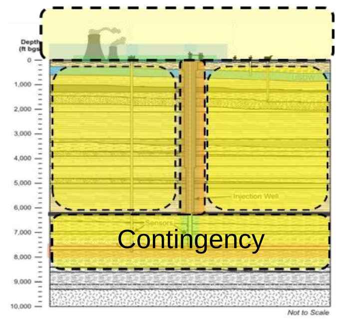
<table>
<tr><th colspan="2">Risk Monitoring</th><th>Atmospheric, A</th><th>Surface/ Near Surface, S/NS</th><th>Reservoir, R</th></tr>
<tr><td colspan="2">4. Contingency</td><td>●</td><td>●</td><td></td></tr>
<tr><td colspan="2">Definition: Monitoring to characterize and track any potential undesired migration or system deviation. Contingency monitoring aims to address risks associated with loss of containment and environmental impacts arising from unintended migration and leakage. It involves additional monitoring for detecting and characterising any migration of CO_2 along well (injector, monitoring well, legacy well), any migration along fault pathways, above-zone fluid migration to the lowest underground water zone, and contamination of surface soils to establish leakage and for potential quantification of any CO_2 released into the atmosphere.
Description: Common contingency monitoring technology used includes seismic, fluid and soil sampling, and depending on the MRV program atmospheric testing such as airborne spectral imaging. Microseismic is common for identifying seismic events due to pressure changes and responses to the storage zone. Small scale events may not be captured in the measured data and/or high noise ratio can interfere with data and create event artifacts. Fluid and soil sampling provide data that can be presented to the public and demonstrate CO_2 containment or leakage. These techniques are limited to specific sampling points and require a large number of sampling points to capture potential CO_2 migration.</td><td colspan="3">Surface/Near-Surface/Reservoir

</td></tr>
<tr><th>Example Technologies</th><th colspan="4">Descriptions</th></tr>
<tr><td>Microseismic</td><td colspan="4">Monitor fracture properties from downhole, surface to subsurface.
Time-lapse monitoring to survey migration of CO_2 plumes.
Identification of potential fractures and faults in the subsurface.</td></tr>
</table>

Table 4-8. Risk assessment for mitigation including risk monitoring zone and examples of technology

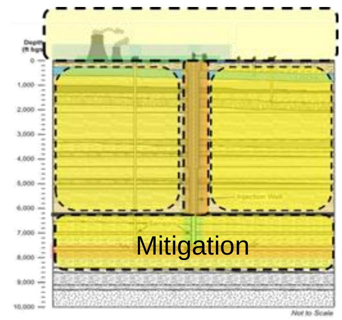
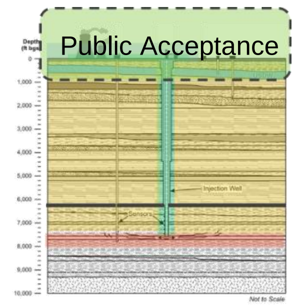
<table>
<tr><th colspan="2">Risk Monitoring</th><th>Atmospheric, A</th><th>Surface/ Near Surface, S/NS</th><th>Reservoir, R</th></tr>
<tr><td colspan="2">5. Mitigation</td><td>●</td><td>●</td><td></td></tr>
<tr><td colspan="2">Definition: Monitoring to track and quantify effectiveness of mitigation measures to control any potential undesired migration or system deviation.
Mitigation monitoring is additional monitoring implemented to assess the effectiveness of controlling the undesired consequences of risk events identified based on the project-specific risk management plan.
Mitigation monitoring involves tracking and quantifying any above zone fluid migration to the lowest USDW zone, contamination of surface soils, and/or release of CO_2 in the atmosphere.
Description: Common mitigation monitoring technologies used are similar to contingency technologies which include seismic, fluid and soil sampling, and depending on the MRV program atmospheric testing such as airborne spectral imaging. These monitoring technologies quantify if there is CO_2 leakage to the surface. These methods are easily interpreted and cover a large monitoring area. Spectral imaging can measure a large area and provides a non-invasive way to monitor the atmospheric zone above the reservoir. Temporal changes and densely forested or populated areas can create false positives for CO_2 changes.</td><td colspan="3">Atmosphere/Surface/Near-Surface

</td></tr>
<tr><th>Example Technologies</th><th colspan="4">Descriptions</th></tr>
<tr><td>Airborne Spectral Imaging</td><td colspan="4">Covers large area, non-invasive</td></tr>
</table>

Table 4-9. Risk assessment for stakeholder/public acceptance including risk monitoring zone and examples of technology

<table>
<tr><th colspan="2">Risk Monitoring</th><th>Atmospheric, A</th><th>Surface/ Near Surface, S/NS</th><th>Reservoir, R</th></tr>
<tr><td colspan="2">6. Public Acceptance</td><td>●</td><td>●</td><td></td></tr>
<tr><td colspan="2">Definition: Monitoring tools to ensure safe storage and system integrity beneficial for increased public acceptance among the local population.
Public acceptance monitoring aims to address operational risk associated with public perception of safe and secure storage. Its significance among other project risks is determined on a per-site basis by the site owners and local operators.
Public Acceptance monitoring during project operations involves inclusion of monitoring technologies that provide important visual assurances of desired system performance for the public, demonstrating containment of CO_2 and quantifying any above-zone fluid migration, soil contamination or release into the atmosphere.
Description: Common public acceptance monitoring technologies used are groundwater and soil sampling. These monitoring technologies are mainly to demonstrate to stakeholders and the public that CO_2 is contained within the storage zone and leakage has not been detected. Gas and soil sampling are common and is easily interpreted to the public. Soil and gas concentration sampling are simple and direct measurement technologies that provide baseline and repeat data. However, natural CO_2 gas can also be detected with this technology and requires frequent testing of the area.</td><td colspan="3">Atmosphere/Surface/Near-Surface

</td></tr>
<tr><th>Example Technologies</th><th colspan="4">Descriptions</th></tr>
<tr><td>Soil Gas Concentrations</td><td colspan="4">Monitoring of soil gas composition to detect increases in CO_2 levels or other indicators of CO_2 leakage</td></tr>
<tr><td>Surface Gas Flux</td><td colspan="4">Monitoring CO_2 flux volumes as indicator of CO_2 leakage to surface</td></tr>
</table>

5.0 Cost Benefit Analysis for Select R&D Technologies

This section considers the monitoring technologies for CCS in the context of their cost-benefit on application for a given project. The development of any monitoring program requires its alignment with site-specific considerations of project phase goals and site-specific conditions affecting the sensitivity of that monitoring technology. The project goals would be different for a research or demonstration project in comparison to a fully commercial storage project as they would attempt to address varied issues of scientific and public concern. Goals would also be dependent on regulatory and industry drivers specific to the region as well as the project phase of concern. Optimized monitoring programs are dynamically adapted to address specific pre-injection, operational and post-injection or closure phase requirements of storage projects effectively. Site-specific conditions affecting the sensitivity of the monitoring technology include the presence of high permeability anisotropy and other geologic and structural features that would affect the operation of that technology in a given site. While these site-specific considerations are well recognised and constitute the site-specific risks for the project, this section attempts to provide a general set of considerations that are aimed to address the six key risk categories systematically. Such definition and evaluation of cost-benefit is extremely useful for the selection of key monitoring and modelling technologies by weighing their risk reduction capability to meet these key objectives of a given storage project.

***Cost benefit matrix* -** The lifecycle benefits generated by each technology is estimated in terms of the risk reduction for the six identified key risk categories. Components of the cost-benefit analysis include the evaluation metrics given in Table 5-1. The ranking scheme employed for monitoring technologies is defined in the Table 5-1 using six discrete levels based on our evaluations from field experience and expert consensus from practitioners in applications from an array of CCS sites around the world. The cost benefit evaluation metrics have been defined to cover a broad scope of the technology's applications in CCS projects. Increasing ranks imply qualitatively improving cost-benefit according to this ranking scheme. The risk category, coverage, TRL, accuracy and reliability metrics are combined to define the relative benefits realized and compared with the unit costs for the different monitoring technologies.

Table 5-1. The subset of six evaluation metrics from the comprehensive Table 2-3 that would be used as inputs for the cost-benefit considerations in the current report.

Cost Benefit Evaluation Metric	Metric Values					
	1	2	3	4	5	6
	Low Cost Benefit --> High Cost Benefit					
Risk Category	1	2	3	4	5	6
TRL	1	2	3	4	5	6
Accuracy/ Resolution	undefined/ experimental	low	med-low	medium	med-high	high
Coverage	undefined	cm	meters	10s meters	100s meters	kms
Reliability (inverse of Operational limitations)	developmental	low	med-low	medium	medium-high	high
Unit Costs ($/m^2)	developmental	$100,000s	$10,000s	$1000s	$100s	$10s

As shown in Table 5-1, individual monitoring technologies can be applicable to manage multiple risk categories. The risk category metric is a simple measure of the number of risk categories that the given monitoring technology serves to address. Higher TRL, and hence more established, technologies would be preferable for implementation in large-scale and commercial-scale projects. Between any two monitoring technologies, all things being equal, the technology that covers a larger area is preferable due to the reduced number of measurement nodes that are needed to cover the plume or area of interest in the storage site. Similarly, the relative benefit offered by a more accurate as well as reliable monitoring technology, would require lesser calibration and handling issues that would add to potential costs of implementation. An important note however is that this evaluation does not prioritize any monitoring technology that may be mandated by regulations for compliance but only considers the benefits and costs in relation to aligning with the desired monitoring objectives. This implies that the monitoring technologies are not distinguished based on their relevance for this evaluation and discrimination between the significance of technologies for any given risk is not pre-determined. The unit costs are typically not often publicly available as cost information for existing storage sites is confidential as well as highly site, time and scale dependent. Hence generic order of magnitude cost information was utilized in the study.

5.1 Unit cost analysis

The combined evaluation of costs and benefits results in the following ranking of different monitoring technologies. While the “ranking” does not serve to imply an “in versus out” criteria, the relative benefits and unit costs balance the consideration for monitoring tool selection to reduce the risk involved in achieving the desired objectives of a CCS project.

The cost benefit analysis evaluation implemented in the current section is meant to serve as a guideline methodology applicable for an improved quantitative project-specific evaluation for monitoring design to manage pertinent risks determined by a risk assessment plan. Since this is not a formal risk assessment, the results of this cost benefit analysis are indicative guidelines of relevant higher value technologies to manage the six determined risk categories. The ranking of monitoring technologies to manage the six key risk categories are discussed below. Radial plots detailing the cost benefit evaluation metrics of the top-ranking monitoring technologies for each risk category help analyze the considerations critical to ultimate technology selection. Project-specific application of the current methodology would bring out valid discriminators to help in technology selection for a well-balanced monitoring scheme that would provide most value while addressing crucial identified risks over the lifetime of the project.

Figure 5-1 gives the cost-benefit comparison of different monitoring technologies that manage the risk of capacity in a storage project. The ranking of the five metrics according to the scale defined in table 5-1 is shown for each of the technologies. In this representation, the unit costs are indicated with negative values while the metrics contributing to the benefits are indicated with positive values. Ideal technologies procure higher ranking that are indicated by the longest columns in the comparison chart. The operational monitoring and distributed acoustic sensing technologies are determined to provide the highest cost-benefit to reduce the risk of capacity determination in a given storage project as shown in Figure 5-1.

Figure 5-2 provides a one-to-one comparison of the six evaluation metrics constituting the cost-benefit analysis for the operational monitoring and distributed acoustic sensing technologies. In the radial comparison plots, fuller circle segments are more desirable for the evaluation metrics with the highest rank represented by three-fourths of a circle. To reduce the risk of capacity determination in a given storage project, while the costs of these technologies are comparable, the reliability of operational monitoring is much higher as shown in Figure 5-2. On the other hand, the distributed acoustic sensing technology can be deployed such that it has higher coverage that would be more beneficial.

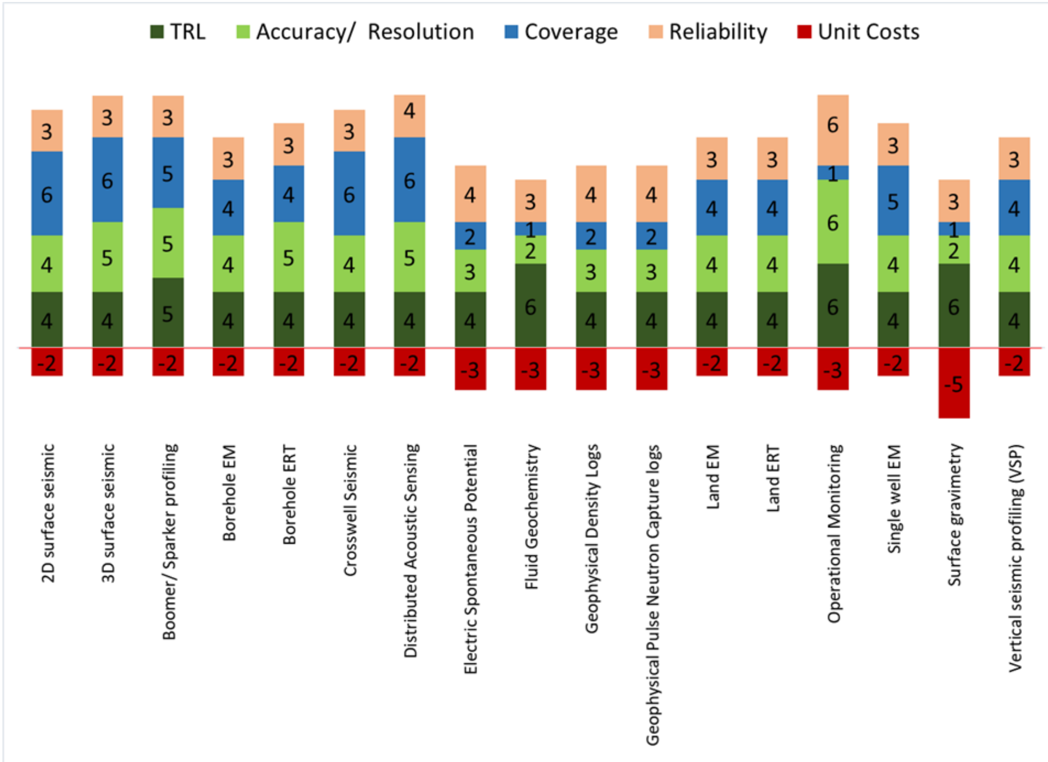


Figure 5-1. Cost-benefit analysis for Risk category Capacity.

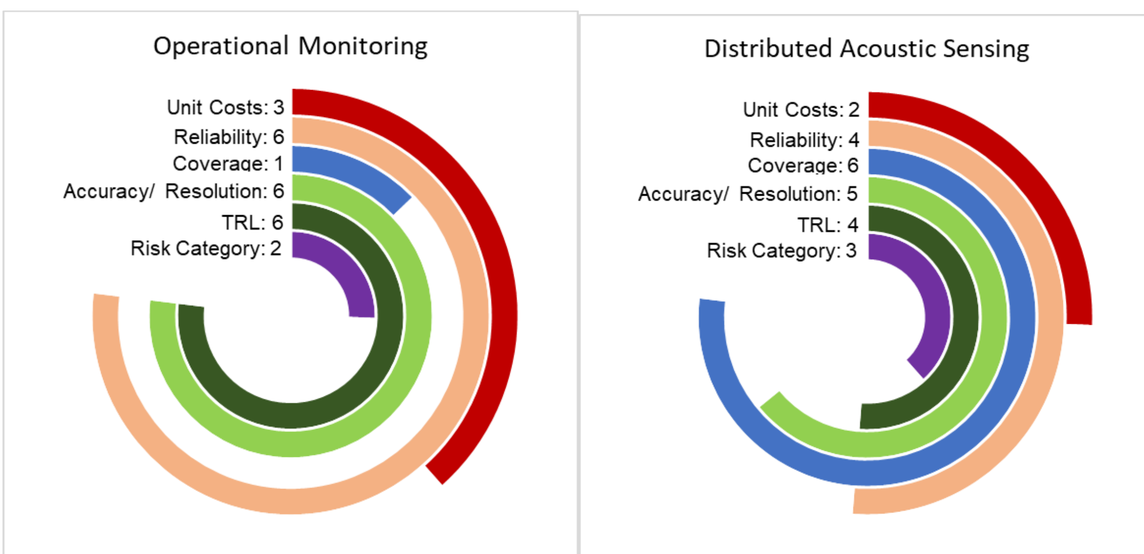


Figure 5-2. Radial plot comparison of top technologies in Risk category Capacity

Monitoring for containment is a critical safety and integrity related objective for storage projects. Figure 5-3 gives the cost-benefit comparison of different monitoring technologies that manage the risk of ensuring CO_2 containment in a storage project. The ranking of the five metrics according to the scale defined in Table 5-1 is shown for each of the technologies. The downhole pressure/temperature sensing and annulus pressure testing technologies are determined to provide the highest cost-benefit to reduce the risk of containment in a given storage project as shown in Figure 5-3. Downhole pressure/temperature gauges within observation wells in the above-zone monitoring interval or AZMI would provide early indication of loss of containment with any sustained pressure increase above the established level of variations. Other technologies such as casing pressure monitoring, groundwater monitoring and tiltmeters follow closely with higher cost-benefit to deploy in order to reduce the risk of ensuring containment. Results of surface deformation from tiltmeters can be useful if they are integrated with other imaging technologies as well as injection (and any production) information.

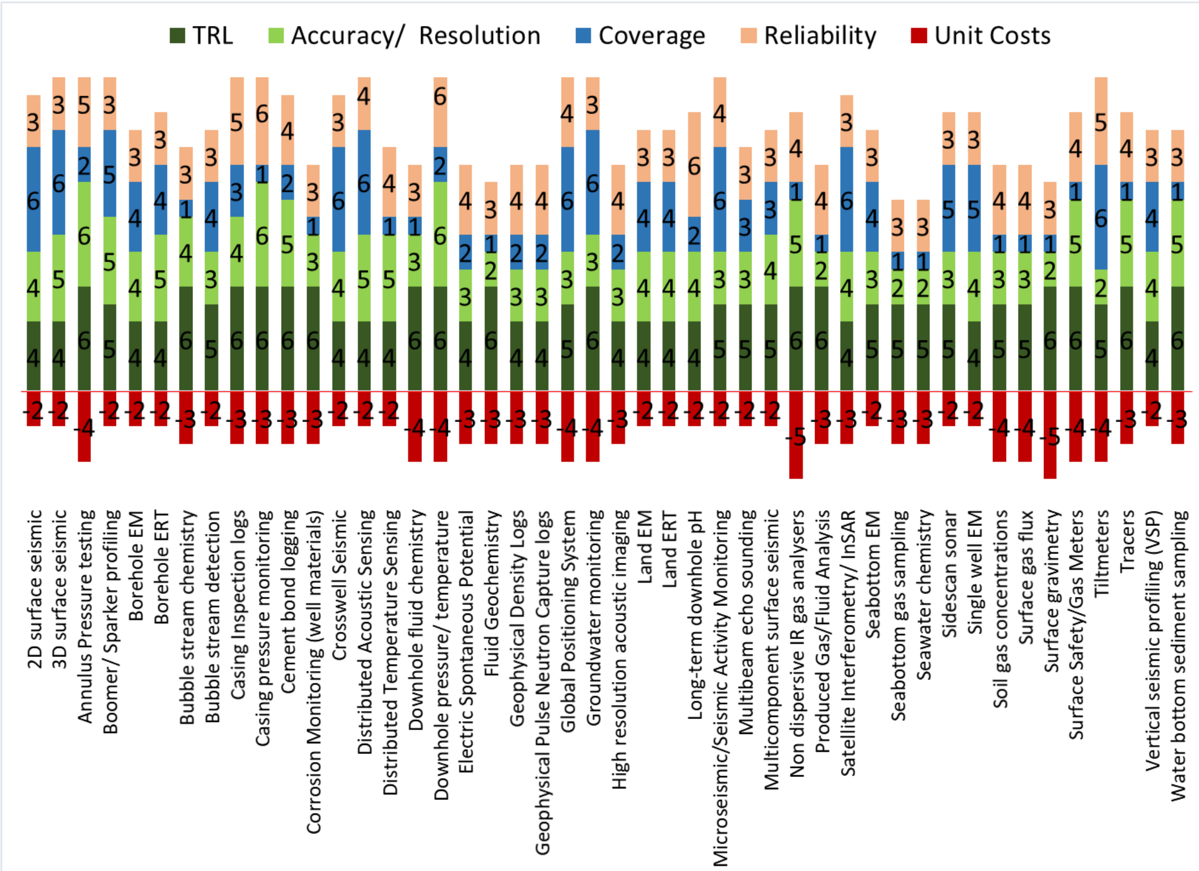


Figure 5-3. Cost-benefit analysis for Risk category Containment.

While typically an array of corroborating monitoring methods is used in CCS projects to track the CO_2 plume in the subsurface as no single technology is absolutely reliable, the cost benefit analysis helps in the choice of technologies to ensure containment. Figure 5-4 provides a one-to-one comparison of the six evaluation metrics constituting the cost-benefit analysis for the downhole pressure/temperature sensing and annulus pressure testing technologies. To reduce the risk of ensuring CO_2 containment in a given storage project, while the costs of these technologies are comparable, the reliability of downhole pressure/temperature monitoring is higher. In addition, downhole pressure/temperature monitoring is also desirable as it has a higher risk category in comparison to annulus pressure testing. Geophysical methods see decreased cost-benefit as they are associated with the challenges of their dependency on geologic settings making it difficult to interpret results and low accuracy.

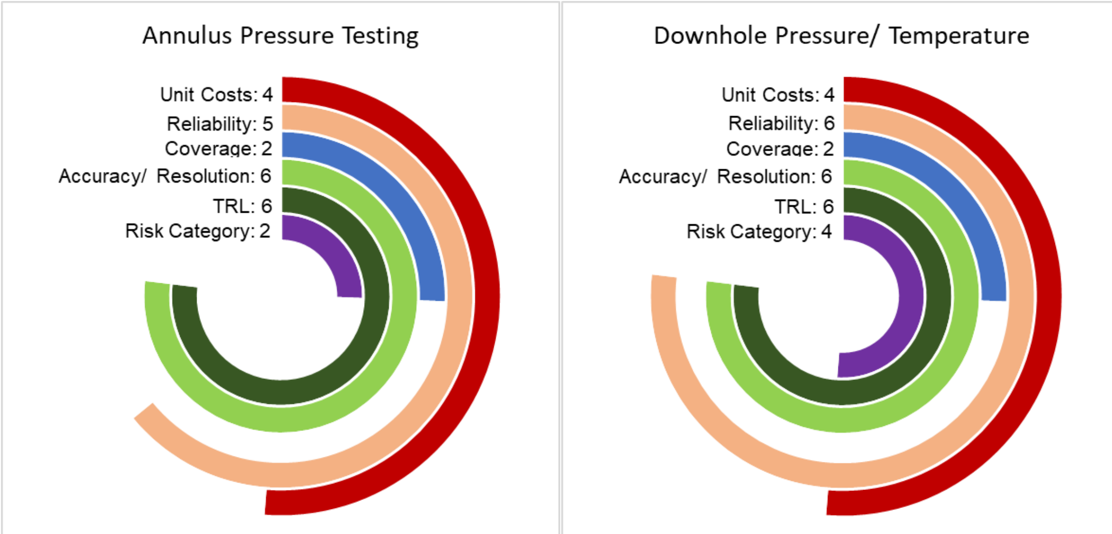


Figure 5-4. Radial plot comparison of top technologies in Risk category Containment.

Routine monitoring for injectivity determination is an important performance metric as the consequence of reduced injectivity implies an increased cost of CO_2 storage per tonne. Costs would escalate due to well workover or remediation activities as well as possible addition of wells and laterals to maintain injectivity. These scenarios also have accompanying MMV activities that would add to the increased storage costs. Figure 5-5 gives the cost-benefit comparison of different monitoring technologies that manage the risk of determining CO_2 injectivity in a storage project. The ranking of the five metrics according to the scale defined in table 5-1 is shown for two technologies typically used for measuring injectivity performance. The downhole pressure/temperature sensing provides higher cost-benefit to reduce the risk of injectivity in a given storage project as shown in Figure 5-5.

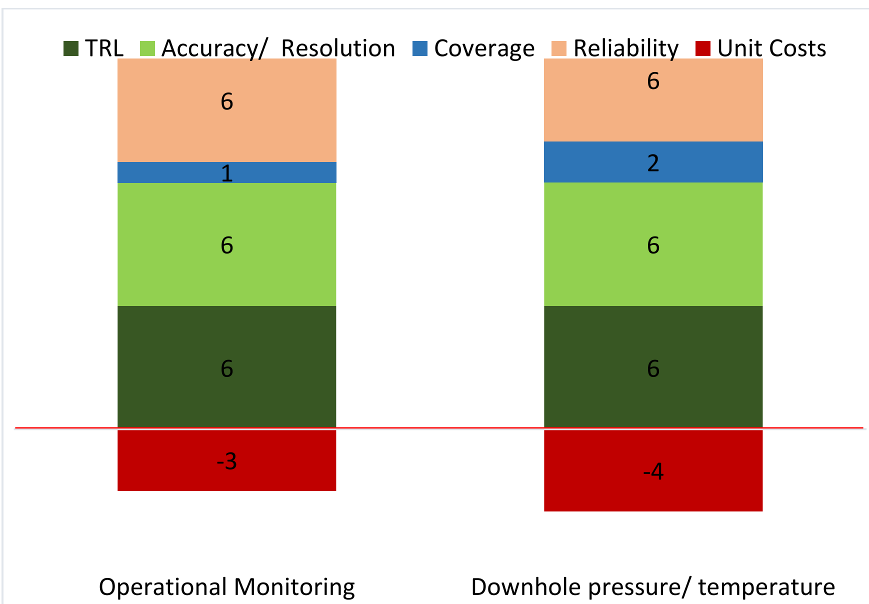


Figure 5-5. Cost-benefit analysis for Risk category Injectivity.

Figure 5-6 provides a one-to-one comparison of the six evaluation metrics constituting the cost-benefit analysis for the downhole pressure/temperature sensing and operational monitoring technologies. While the reliability, coverage and accuracy are comparable, the cost of deploying downhole pressure/temperature monitoring is lower. Operational monitoring includes downhole pressure/ temperature monitoring along with tracking other parameters such as injection flow rate, fluid density and composition making it an order of magnitude more expensive as shown in Figure 5-6. In addition, downhole pressure/temperature monitoring is also desirable as it has a higher risk category in comparison to operational monitoring.

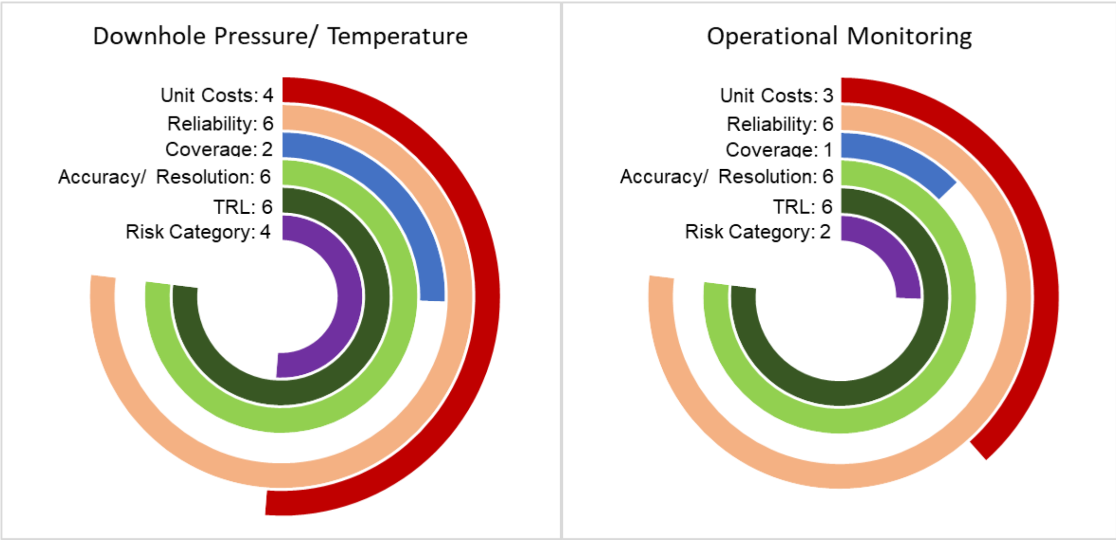


Figure 5-6. Radial plot comparison of top technologies in Risk category Injectivity.

The role of contingency monitoring is to substantiate the performance of any monitoring technology and as a safeguard to verify the effectiveness of mitigation or remediation measures under unlikely events of unexpected storage or monitoring performance. Figure 5-7 gives the cost-benefit comparison of different monitoring technologies that manage the risk of ensuring contingency in a storage project. The ranking of the five metrics according to the scale defined in Table 5-1 is shown for each of the technologies. The downhole pressure/temperature sensing and annulus pressure testing technologies are determined to provide the highest cost-benefit to reduce the risk of contingency in a given storage project as shown in Figure 5-7. The technologies that were determined to provide higher cost-benefit for reducing the risk for containment as also seen to perform equivalently for contingency monitoring. Downhole pressure/temperature gauges within observation wells in the above-zone monitoring intervals or AZMI features as an effective contingency monitoring technology as well by providing early indication of loss of containment without penetrating the injection zone. Other technologies such as groundwater monitoring and tiltmeters follow closely with higher cost-benefit to deploy in order to reduce the risk of ensuring containment. These methods can be substantiated by optimized deployment of time-lapse seismic methods which are more expensive but provide higher coverage.

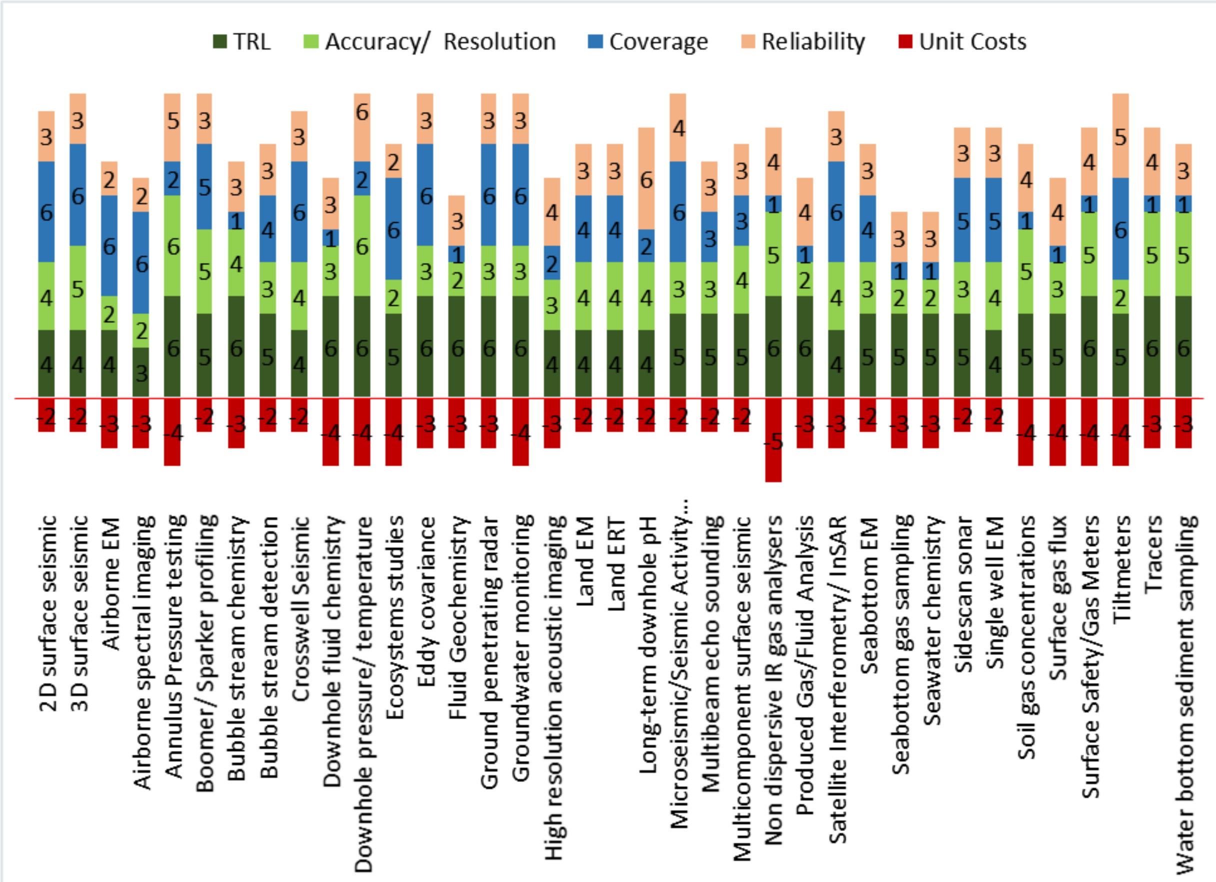


Figure 5-7. Cost-benefit analysis for Risk category Contingency.

Figures 5-8 and 5-9 provide a one-to-one comparison of the six evaluation metrics constituting the cost-benefit analysis for the top monitoring technologies with the highest determined cost-benefit to reduce the risk associated with contingency monitoring in a storage project. While the costs of these technologies are comparable, the reliability of downhole pressure/temperature monitoring is the highest. Downhole pressure/temperature monitoring and groundwater monitoring have a higher risk category in comparison to annulus pressure testing and tiltmeters. Downhole pressure/temperature monitoring and annulus pressure testing have the highest accuracy/ resolution but lower coverage in comparison to groundwater monitoring and tiltmeters.

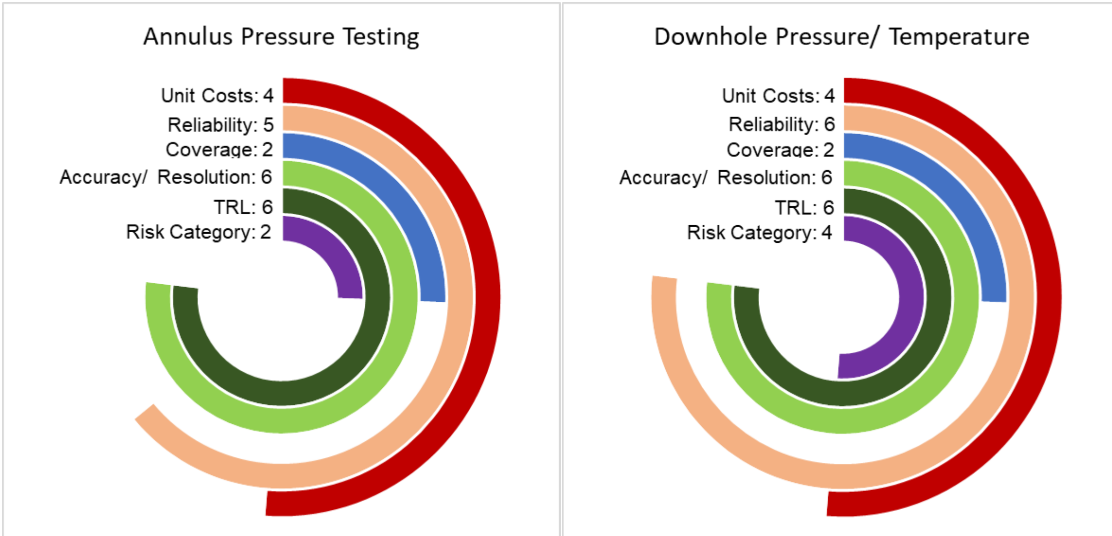


Figure 5-8. Radial plot comparison of top 2 technologies in Risk category Contingency.

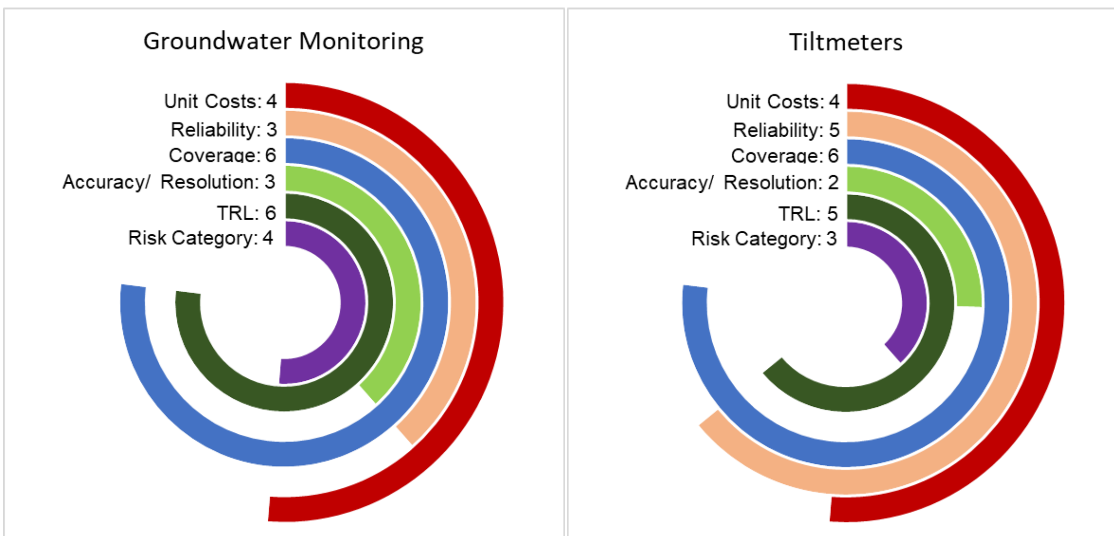


Figure 5-9. Radial plot comparison of other top technologies in Risk category Contingency.

Monitoring technologies for mitigation are employed in the unlikely event of loss of containment, capacity or injectivity. These technologies would ensure the decrease in the likelihood or severity of the undesirable consequences of any of these risk events by measuring relevant parameters to assess the success of the mitigation strategy. Figure 5-10 gives the cost-benefit comparison of different monitoring technologies that manage the risk of ensuring mitigation in a storage project. The ranking of the five metrics according to the scale defined in Table 5-1 is shown for each of the technologies. The downhole pressure/temperature sensing, distributed temperature sensing and 3D surface seismic technologies are determined to provide the highest cost-benefit to reduce the risk of ensuring mitigation in a given storage project as shown in Figure 5-10.

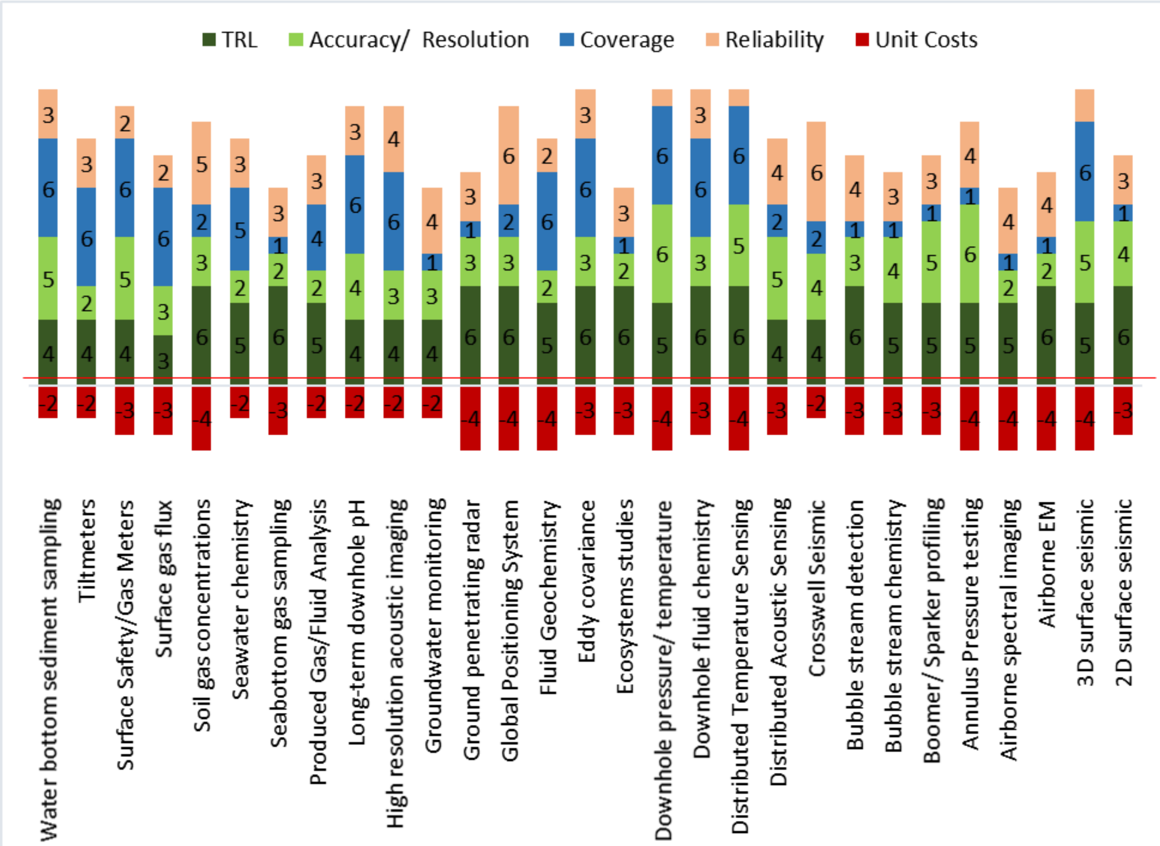


Figure 5-10. Cost-benefit analysis for Risk category Mitigation.

Figure 5-11 provides a one-to-one comparison of the six evaluation metrics constituting the cost-benefit analysis for the top monitoring technologies with the highest determined cost-benefit to reduce the risk associated with ensuring mitigation in a storage project. The unit cost, accuracy/ resolution as well as reliability of downhole pressure/temperature monitoring is the highest among the three technologies. 3D seismic provides the highest coverage and is hence effective to ensure mitigation while also being non-invasive.

Figure 5-11. Radial plot comparison of top technologies in Risk category Mitigation.

Monitoring technologies for public acceptance are employed to address site-specific concerns of the local population in the region. While all monitoring technologies contribute to managing performance, safety and integrity concerns, some technologies are more focused towards important visual assurances of desired system performance for the public. Figure 5-12 gives the cost-benefit comparison of different monitoring technologies that manage the risk of public acceptance in a storage project. The ranking of the five metrics according to the scale defined in Table 5-1 is shown for each of the technologies. The groundwater monitoring and global positioning system technologies are determined to provide the highest cost-benefit followed by satellite interferometry or InSAR to reduce the risk of ensuring public acceptance in a given storage project as shown in Figure 5-12. As expected, both the groundwater monitoring, that ensures that the local underground source of drinking water remains unaffected by the storage operations, and InSAR, that measures any vertical ground movement, are thus found to be highly cost-beneficial tools to convince public opinion that CCS does not pose a hazard to health and to the environment in their region. Robust baseline characterization and ‘zero’ measurements typically form the desired operational performance for all monitoring technologies implemented to manage the risk of public acceptance. Hence groundwater monitoring to ensure no CO_2 leaks into the shallowest underground source of drinking water is valuable and needs to be included in the monitoring plan if the risk of public acceptance is significant at a given CCS site while geomechanical integrity risks need to be managed by including technology such as InSAR to ensure zero vertical ground movement.

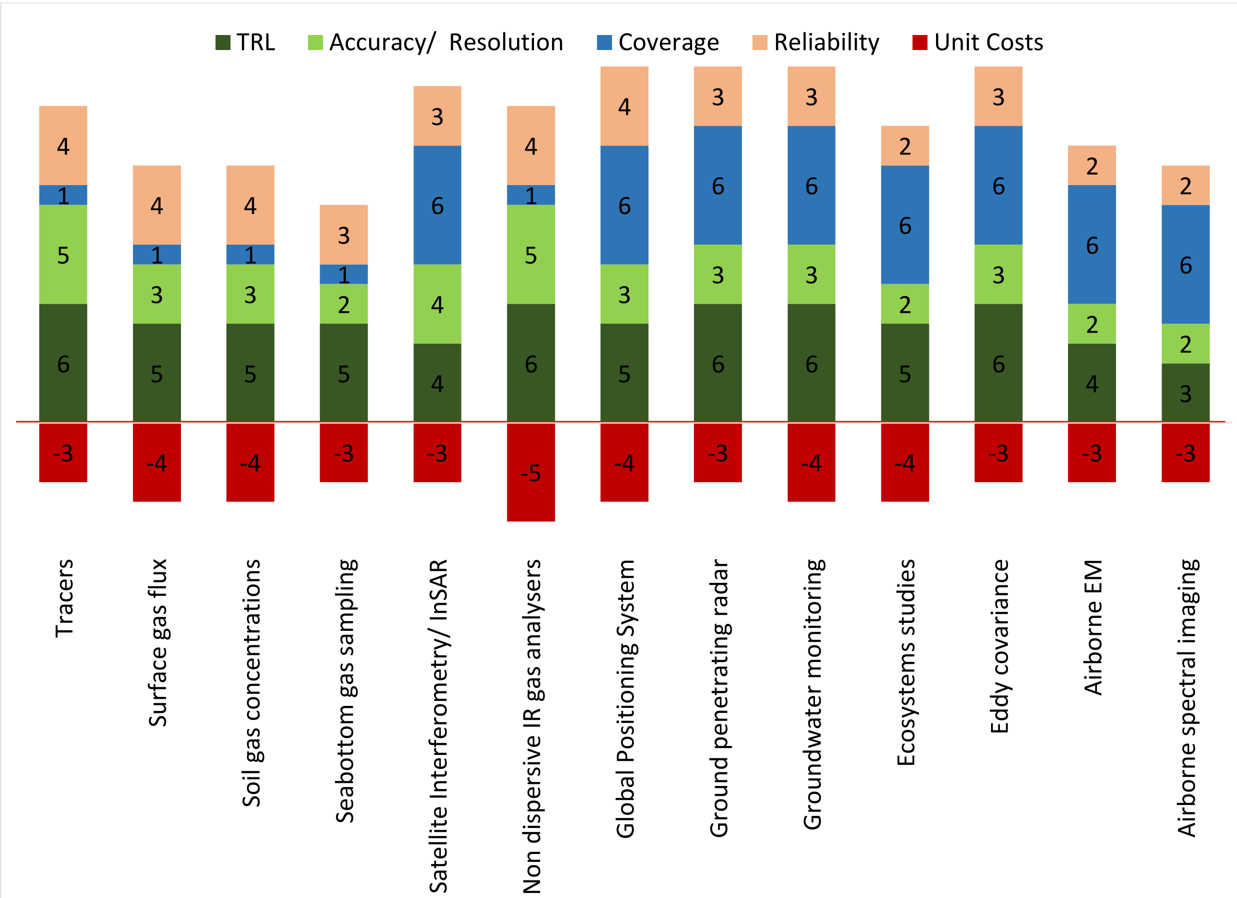


Figure 5-12: Cost-benefit analysis for Risk category Public Acceptance.

Figure 5-13 provides a one-to-one comparison of the six evaluation metrics constituting the cost-benefit analysis for the top monitoring technologies with the highest determined cost-benefit to reduce the risk associated with reducing the risk of public acceptance in a storage project. All the three top monitoring technologies in terms of their cost-benefit are seen to provide ideal site-wide coverage. InSAR has higher unit costs for similar reliability of the technology in comparison with the groundwater monitoring and global positioning system. Groundwater monitoring is the most mature technology among the three with the highest TRL.

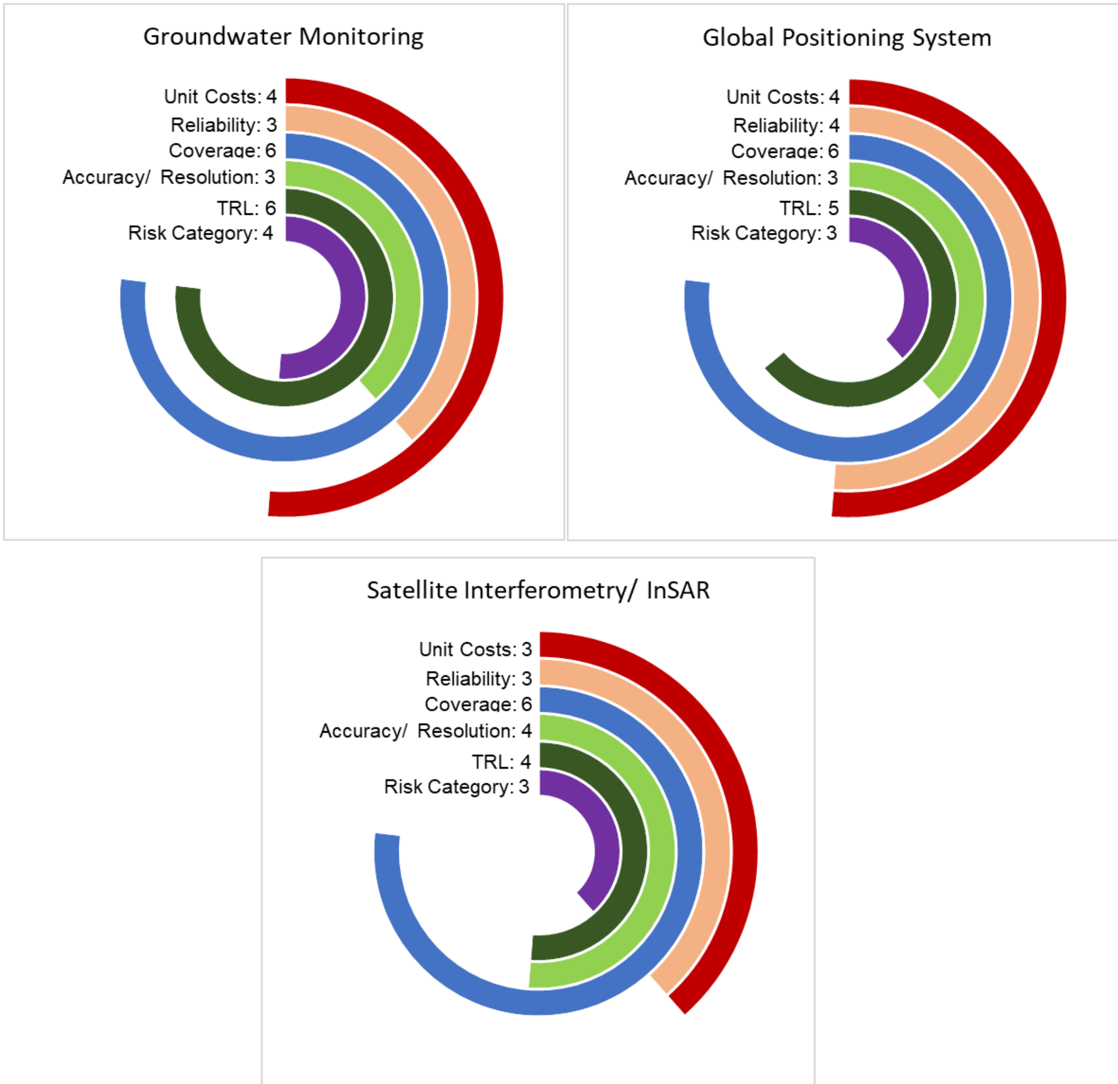


Figure 5-13. Radial plot comparison of top technologies in Risk category Public Acceptance.

Although many monitoring techniques have been developed and improved upon over the past decade, pressure-based monitoring technology provides high benefit/cost ratio and has the high potential of reducing multiple risk categories while being relatively simple in terms of the implementation and processing involved. This is also validated by the industry consensus that all CCS projects consider subsurface pressure as the most valuable monitoring method. While groundwater monitoring and other atmospheric and near-surface monitoring technologies are seen to provide high cost-benefit for reducing certain risks, especially public acceptance, these technologies require successful establishment of stable pre-injection baseline, and get scaled back during operations. In such situations, the reservoir zone and above-zone monitoring suite of technologies ensure containment and leakage risks are well-managed and bolster atmospheric and near-surface monitoring observations to address stakeholder concerns.

Monitoring data is key to ensure safe and secure geologic storage over time for any well-operated project. While no single monitoring technology is ideal in its performance with respect to the metrics defined in section 2.3, there are some that clearly perform better to address certain project risks. Systematic and educated consideration of monitoring technologies based on pertinent project risks complement correct site selection and operations to ensure dependable economics for commercial-scale projects. Regulatory and expert guidance provided for geologic storage strongly recommend site-specific evaluation but there is lack of an overall methodology to perform a cost-benefit analysis at any given project phase to address monitoring tool selection to reduce specific project risks. The cost-benefit analysis presented here is intended to be used as a guideline for the selection of an optimal suite of monitoring technologies at other potential storage sites to address their site-specific project goals. A systematic site-specific risk management plan would enable the tailoring of the MMV plan to design considerations for selection of optimal monitoring technologies to address specific project goals under consideration.

Evaluation of costs for monitoring technologies versus CCS total project budgets

The budget allocation for the monitoring plan for a given storage project is highly dependent on the objectives of the project. Research projects tend to indulge more in their monitoring and verification plan budget in all phases of the project in comparison to commercial projects which tend to implement the minimum regulatory requirements for conformance and containment. Typical monitoring costs do not form a significant portion of the site operating expenses. In the Shell Goldeneye storage project (Cotton et al., 2017), which was a pilot demonstration project in the UK designed to store 15 Mt CO_2, monitoring costs during injection and post-injection equated to 7% of the total CO_2 capture and storage expenses (Source: Shell UK Limited, 2015). Among the different monitoring technologies employed, seismic methods formed the greatest proportion of the monitoring costs, from 60% to 86%.

In the case of the AEP Mountaineer pilot demonstration project in the Appalachian Basin region of the United States, Figure 5-14 gives the proportion of different types of monitoring technologies employed during different phases of the project. Table 5-2 lists the different types of monitoring technologies implemented in the project. While no atmospheric monitoring technologies were implemented in this project, the ratio of reservoir zone versus surface or near-surface monitoring technologies clearly varies, as seen in Figure 5-14, to assuage the differing objectives through the initial baseline until the post-injection or site closure phase of the project. Reservoir monitoring technologies were the focus of the monitoring activities, but their proportion was higher during the baseline characterization and post-injection phases to provide better assurance of (and in turn reduce the associated risk of) capacity and conformance.

Table 5-2. List of monitoring technologies implemented for the entire lifecycle of the AEP Mountaineer pilot project in the Appalachian Basin of the United States during 2009-2011.

Monitoring Technology	Atmosphere	Surface/Near-Surface	Reservoir
Injection Well Flow and P/T Monitoring			X
Corrosion Monitoring		X	X
Surface CO2 Monitoring	X	X	
Soil Gas Tracer Surveys		X	
Shallow GW Monitoring		X	
External MIT			X
Pressure Falloff Testing			X
Microseismic Monitoring		X	X
Wireline Logging/PNC			X
Deep Well Fluid Monitoring			X
Cross-Well Seismic		X	X
Deep Well P/T Monitoring		X	X

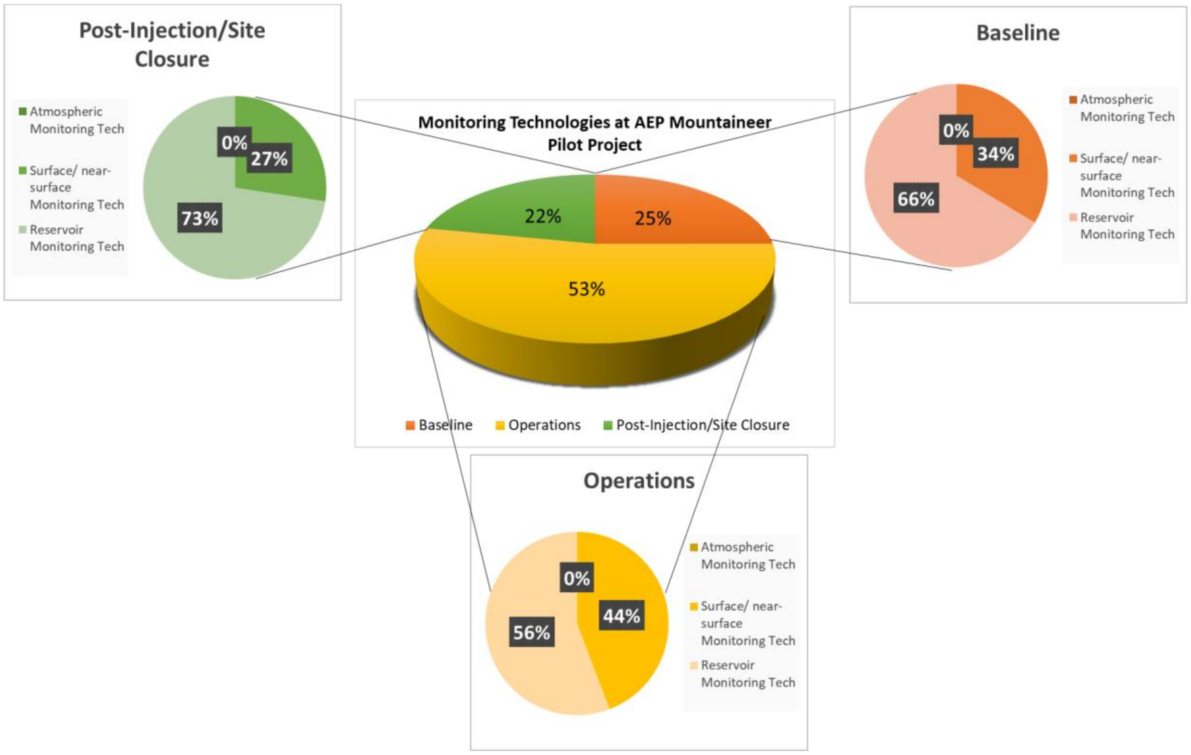


Figure 5-14. Contribution of different types of monitoring technologies over the lifecycle of the AEP Mountaineer pilot project.

5.2 Regulatory monitoring requirements analysis

Depending on location, many CO_2 storage monitoring and modelling programs may be dictated by regulations. The case studies in this report provide a summary of the impact of regulations on different CO_2 storage projects:

- The Midwest Regional Carbon Sequestration Partnership Niagaran Reef CO_2-EOR Industrial-Scale Demonstration was completed in Michigan, USA. The injection wells were subject to U.S. Environmental Protection Agency (USEPA) Underground Injection Control (UIC) regulations for Class II injection wells. Class II wells are associated with oil & gas operations. There are several hundred thousand Class II UIC wells in the U.S., and the Class II regulations are well established. Most of the MRCSP Niagaran Reef injection wells had pre-existing Class II permits. Class II regulations have requirements for metering injection, wellbore integrity, and reporting. The MRCSP site recently completed an MRV plan for U.S. Federal "45Q" incentives for CO_2-EOR.
- The Quest CCS Project in Alberta, Canada, is subject to Alberta CCS Statutes Amendment Act regulations. These regulations require submission of a monitoring, measurement, and verification (MMV) plan to the Alberta Energy Ministry. However, the requirements of the MMV plan are not specifically outlined in the regulations. The Quest monitoring plan includes a tiered monitoring approach that allowed modification of the monitoring program based on results obtained as the project progressed.

- The Sleipner CCS Project is subject to Norwegian Petroleum Law. These laws cover health, safety, and protection of the environment for offshore oil and gas operations in the North Sea. Since the Sleipner CCS Project started before many CO_2 storage regulations were considered, many of the traditional oil & gas regulations were enforced for the project. Specific regulations for CO_2 storage monitoring were defined in 2014 in Norwegian Petroleum Law. These regulations provide the operator with a degree of freedom in the monitoring program (Furre et al, 2017).
- The In Salah CCS project was completed in central Algeria. The project was designed to set precedents for the regulation and verification of CO_2 storage (Ringrose et al., 2013). The In-Salah CCS project was designed to comply with the EU CCS Directive on the Geological Storage of Carbon Dioxide (Directive 2009/31/EC).
- The Mountaineer Product Validation Facility CCS Project was completed in West Virginia, USA. The project was subject to USEPA UIC Class V regulations for experimental wells since the project was completed before Class VI CO_2 Sequestration regulations were released. However, many of the monitoring requirements were influenced by the pending Class VI regulations and West Virginia Department of Environmental Protection Class II UIC program. While the project had specified 20 years of post-injection monitoring, a combination of monitoring and modelling was used to support closure 6 years after injection ceased.

Overall, it appears that most CO_2 storage projects will require negotiation of monitoring plans with regulatory agencies. For cost-benefit, operators are well served to include some degree of strategic flexibility in their monitoring plans such as tiered monitoring plans, forward modelling, quantitative thresholds, and material impact criteria.

5.3 Cost benefit risk reduction assessment

While monitoring costs may be directly quantified, the benefit of these technologies is difficult to objectively quantify, especially in terms of the different stakeholders. Consequently, a stakeholder perspective was examined for the cost benefit relationship between CO_2 storage monitoring and risk reduction. Identifying key stakeholders is an important step in CCS public outreach planning (IEAGHG, 2013; U.S. DOE-NETL, 2017). A variety of stakeholders that may be involved in the development of a CO_2 storage project: executive leadership for an industrial CO_2 source, project manager for the overall CCS project, financial backers/insurers, technical consultants, monitoring technology vendors, landowners, local community/residents, non-governmental organizations, regulators, oil & gas operators, research scientists, local government, and national government.

Key risks, benefits, and “red flags” were identified for these stakeholders (Table 5-3). Monitoring options and costs were then listed for each stakeholder category. Overall, the stakeholder-based cost benefit analysis illustrates that many of the people involved in project execution may be concerned with deployment, technical performance, and costs. The local landowners, workers, regulators, and community are likely concerned with leakage, impact to the environment, and safety. These risks may be addressed with relatively low-moderate cost monitoring technologies. Researchers and government are concerned with more wide-ranging risks with higher costs like injectivity, storage capacity, CO_2 plume migration, subsurface effects of injection, and leakage.

Table 5-3. Stakeholder Cost-Benefit Risk Reduction Analysis.

Stakeholder/Perspective	Key Risks	Red Flags	Monitoring Options	Monitoring Costs	Key Benefits
Executive, Industrial CO_2 Source	Costs, liability,safety, schedule, publicity	Safety incidents, leakage, cost overruns	System monitoring, wellbore integrity, high visibility surface monitoring	\$10,000s-\$100,000s	Ensuring system performance, regulatory compliance, environmental stewardship, controlling costs, verification of storage security, public assurance, worker safety, system reliability, accounting for incentives
C-Storage Project Manager	Costs, schedule, installation, performance, regulations, maintenance, design, etc.	Safety incidents, leakage, cost overruns, project performance			
Financial Backer/Insurer	Costs, liability, publicity, long-term security, regulations, leakage	Safety incidents, leakage, cost overruns, project performance			
Technical Consultant	Technology deployment, meeting regulations, satisfying client, costs	Technology failure, client dissatisfaction			
Monitoring Tech. Vendor	Technology performance, costs, technical challenges, installation & deployment, client satisfaction	Technology failure, client dissatisfaction			
Landowner	Leakage, reduction of property value, impact of field work, pipelines, wells, wellbore integrity, traffic, safety	Well leakage, ecosystem effects, wellbore integrity, accidents	Surface, near surface, safety, and wellbore integrity monitoring	\$10,000s-\$100,000s	Protecting environment, safety, reducing carbon emissions, economic benefit to local community, jobs, CO2-EOR revenue from royalties
Local Community & Residents	Protection of near surface resources, leakage, catastrophic failure, environmental impact, traffic	Safety incidents, any leakage, exclusion from siting process, unexpected field work			
Non-Governmental Org.	Natural resources, environment, population, long-term climate change	Leakage, safety incidents, project performance, environmental impact			
Regulator	Meeting regulations, timely submittal, documentation, regulated limits, protection of near surface resources	Violations of regulations, safety incidents, leakage, environmental impact	Near surface, reservoir, wellbore system monitoring	\$10,000s-\$100,000s	Meeting regulations, worker safety, protecting environment, revenue from royalties/mineral rights, jobs, technology progress
O&G operator	Wellbore integrity, CO2 migration into reservoirs, competition for EOR, mineral rights, pore space ownership	CO2 interference with existing oil and gas operations and/or regulations, leakage			
Academic Research Community	Subsurface physical processes, research grants, accuracy, technology effectiveness	Technical errors, failure of technology, project performance, uncertain results	Reservoir monitoring	\$100,000s-\$1,000,000s	Knowledge sharing, advancing science, reducing GHG emissions, protecting human health and environment
Local Government	Local population opinion	Bad publicity, public resistance, safety incidents, leakage, project performance, environmental impact	Capacity, containment, safety	\$1,000,000s-\$10,000,000s	Reducing regional GHG emissions, protecting human health and environment, safety
National Government	National policy, economic development, protection of human health and environment				

6.0 Conclusions

This report describes how a cost-benefit analysis of geologic CO_2 storage monitoring and modelling technologies may effectively address project risks at manageable costs. The analysis was based on the collection of practical data and experience from CO_2 storage projects. Specific metrics were used to evaluate monitoring methods to provide a quantitative measure of cost-benefit. The results demonstrate that there are opportunities to reduce costs in CO_2 storage monitoring operations, allowing for safe development of commercial CO_2 storage projects that provide meaningful reductions in CO_2 emissions. However, projects may benefit from including systematic cost-benefit analysis in monitoring plans, including flexibility in monitoring programs, and streamlining the operational monitoring schedules.

6.1 Progress in CO_2 storage monitoring

A literature review suggests there are thousands of technical articles available on CCS monitoring and modelling. Perhaps no industry is confronted with as many choices as those tasked with designing a CO_2 monitoring program. This can be especially overwhelming to industry decision makers. The majority of technical research (55%) appears to be focused on the reservoir zone, with 24% articles on the near-surface, and 21% of research articles on the atmospheric monitoring zone. However, a timeline of CCS research and major projects demonstrates that CCS projects have progressed from research pilot-scale tests in ~1990-2010, to more industrial scale projects from 2010-2019. The large industrial-scale projects have moved into routine operations, trimming back the number of monitoring technologies and frequency of monitoring events. Several major pilot-scale projects and ongoing initiatives have helped establish familiarity and confidence in CO_2 storage monitoring applications.

There are over 50 different monitoring technologies that are currently deployed for CO_2 storage projects. These methods have different monitored zones, equipment requirements, pre- and post-processing requirements, frequency of sampling, domain monitored, accuracy/resolution, technology readiness level, spatial coverage, costs, risk addressed, advantages, and limitations. These metrics provide a basis for understanding of the general features of the monitoring technologies. However, there are many different deployment options that must be considered for site specific issues.

The integration of monitoring and modelling for CO_2 storage provides an opportunity to confirm modelling predictions with monitoring data. This provides confidence in understanding the subsurface CO_2 storage process. Options for modelling include analytical/semi-analytical models, proxy models, simplified equivalent numerical models, and detailed 3D numerical models. Many CO_2 storage modelling studies as well as field experiences have thus helped improve our understanding of the geophysical processed associated with geologic carbon sequestration.

Several recent cost benefit studies provide examples of how a cost-benefit analysis may be integrated into risk assessment, monitoring program development, and operations. These approaches may include a tiered monitoring strategy, forward modelling, material impact analysis, and/or Boston Square analysis. However, there is no well-established methodology for cost-benefit analysis.

6.2 Technology readiness level of monitoring technologies

There are several systematic TRL approaches to track the technical readiness of technologies, dating back to the space exploration TRL model by NASA in the 1980s. These TRL rating schemes translate to CO_2 storage applications in a different manner, since much of the CO_2 storage technology can only be proven in the field. The TRL of CO_2 storage monitoring technologies appears to be suitable for supporting large-scale industrial CO_2 storage projects. Fundamental and more established methods in CCS operations like operational monitoring, wireline deployed well logging tools, downhole pressure/temperature monitoring, and well integrity related monitoring show higher ratings. Many of the CCS monitoring technologies such as seismic monitoring, operational pressure and temperature monitoring, fluid sampling have higher TRLs already as they have been borrowed from existing oil and gas experiences. Challenges remain for monitoring large CO_2 storage projects, and experts on CO_2 storage believe there is room to refine and improve CO_2 monitoring technologies.

6.3 Monitoring costs

The project reviews of several large-scale CO_2 storage monitoring programs illustrate several conclusions regarding the cost-benefit potential for CO_2 storage:

- There is a large range in monitoring costs: from $10,000s for routine operational pressure and temperature monitoring to $1,000,000s for 4D seismic monitoring. Thus, it is difficult to interpret the cost-benefit ratio for these methods.
- Economies of scale are evident for monitoring programs. As projects inject greater volumes of CO_2 and streamline monitoring programs, costs on a tonne basis decrease.
- It is difficult to separate capital costs of system construction, well drilling, site characterization, administrative support, and technical support.
- Research-oriented pilot-scale projects had fairly high costs to validate technology, but there is a clear opportunity to reduce monitoring costs as project move to routine injection operations.
- Some of the early projects were not subject to extensive regulations and had simpler monitoring programs with lower costs.
- Monitoring costs are a small fraction of the entire CCS project, especially when compared to capital and operating costs for CO_2 capture and compression where there may be little opportunity to reduce costs.
- Many of the monitoring methods have reasonable costs compared to the costs of drilling and constructing deep wells, pipelines, and compression facilities.

Only a few projects have completed the full baseline, operational, and post-injection site closure monitoring. However, these projects provide examples of opportunities to streamline monitoring operations and costs, especially in the post-injection site closure period. Analogs for CO_2 storage also provide examples of the types of monitoring that may be required for very long-term CO_2 monitoring efforts.

CO_2 storage monitoring technologies provide options to address site-specific risks in terms of accountability for injected CO_2, regulatory requirements, leakage detection, and assessment of CO_2 migration. Monitoring technologies are available to address the capacity and containment of the CO_2, monitoring and regulation of injectivity, the potential migration paths of a CO_2 plume, the quantification of the plume migration, the demonstration and public acceptance of safe and effective storage.
Site specific conditions will require a tailored monitoring program that focuses on atmospheric, surface/near-surface, and reservoir monitoring technologies to measure direct and indirect injection and migration of CO_2.

6.4 Cost-benefit relationship to reducing project risks

While the costs for monitoring technologies can be quantified, the benefit can be difficult to measure. This makes definition of the cost-benefit ratio for CO_2 storage a challenge to describe. Commercial, industrial-scale CO_2 storage projects on the order of 1 Mt CO_2/year appear to have converged on monitoring costs of $1-4 million USD per year. The CO_2 storage monitoring costs are a small fraction (<5%) of most CCS projects overall budgets, especially in comparison to capital and operating costs for carbon capture. Some projects with lower capture costs (like ethanol plants and gas processing) may have higher relative monitoring costs, because the capture costs are low. “Hidden costs” related to capital expenses like well construction, site characterization, technical support, and administrative costs are often difficult to depict in cost analysis.

Ranking the combined evaluation of costs and benefits provides a method to depict the cost-benefit of different monitoring technologies. The “ranking” does not provide a definitive criteria, but the relative benefits and unit costs balance the consideration to reduce the risk involved in achieving the desired objectives of a CCS project. CO_2 monitoring techniques have been developed and improved upon over the past decade. Pressure-based monitoring technology provides a high benefit/cost ratio and the potential to reduce multiple risk categories while being relatively simple in terms of the implementation and processing involved. Industrial CCS project managers consider subsurface pressure and temperature as the one of most valuable monitoring methods. Groundwater monitoring and other atmospheric and near-surface monitoring technologies are also considered to provide high cost-benefit for reducing certain risks, especially public acceptance.

While no single monitoring technology is ideal in its performance with respect to the performance metrics, there are some that clearly perform better to address certain project risks. The cost-benefit analysis presented in this study may be used as a guideline for developing optimal monitoring programs to address specific project goals under consideration. Monitoring programs also need to consider regulatory requirements, as evidenced in the project case studies. CO_2 storage projects will likely require negotiation of monitoring plans with regulatory agencies and operators are well served to include some degree of strategic flexibility in their monitoring plans such as tiered monitoring plans, forward modelling, quantitative thresholds, and material impact criteria.

6.5 Knowledge gaps

CO_2 storage technologies are still developing. There are no projects at the 50-100 Mt scale to provide examples of monitoring several hundred square kilometer areas. Accurate detection of CO_2 distribution in subsurface remains a challenge with high costs and limited benefit at times. It appears that comprehensive imaging injected CO_2 in the subsurface is a real challenge which is more significant during the early project stages when there is little quantity of CO_2 injected into the target reservoir. At times, this has limited material benefit to a project. Projects could rely on geologic system with less costly monitoring. Other key knowledge gaps include the following:

- Specific thresholds to help control monitoring costs, especially for delineating the CO_2 plumes and pressure fronts in terms of CO_2 saturation levels and pressure changes.
- Methods for processing the large amount of data that newer monitoring technologies output more for commercial CO_2 storage operations.
- Methods for processing and interpretation data from some geophysical monitoring technologies provide clear results and control costs of ongoing processing and interpretation.
- A systematic or standardized methodology for cost-benefit analysis may be integrated into site characterization, risk analysis, modelling, monitoring program development, and system design.
- Options for confirming the monitoring/modelling predictions rather than exhaustive delineation of the CO_2 in the subsurface.
- Threshold and forward modelling approaches to design monitoring programs that consider the material impact of CO_2 migration in relation to the monitoring technology.
- Criteria for demonstrating plume stability where geologic conditions may result in long-term CO_2 migration within a reservoir but no leakage out of reservoir.
- Systematic and process driven approaches to CO_2 monitoring programs with tiered cost-benefit analysis to aid in managing project risk, costs, regulatory requirements, and field operations.
- Monitoring strategies for sites with many legacy oil and gas wells and wellbore integrity issues.
- Understanding of stakeholder acceptance risks for CO_2 storage project managers in relation to performing near-surface and atmospheric monitoring.

6.6 Path forward

Overall, there is confidence in the array of monitoring technologies available for CO_2 storage projects, and the path forward for implementing safe CO_2 storage projects appears stable. Current operational CO_2 storage projects have been able to streamline their monitoring programs, focus on the most useful monitoring methods that address project specific risks, and control costs. This trend is likely to continue as more industrial scale projects become operational. More standardized monitoring programs are likely to be deployed in regions with many projects that have similar geologic settings. There remains opportunity for technology refinement and improvement. Offshore monitoring technologies, advanced sensors, automated data processing/collection methods, and options to confirm CO_2 plume extent without deep boreholes are areas where monitoring and modelling of CO_2 storage have additional potential for improving the cost-benefit ratio of reducing risk.

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Evaluating technology options to mitigate greenhouse gas emissions

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