Plains CO_2 Reduction (PCOR) Partnership
Energy & Environmental Research Center (EERC)

BEST PRACTICE FOR THE COMMERCIAL DEPLOYMENT OF CARBON DIOXIDE GEOLOGIC STORAGE: THE ADAPTIVE MANAGEMENT APPROACH

Plains CO_2 Reduction (PCOR) Partnership Phase III
Task 13 – Deliverable D102/Milestone M59

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EXECUTIVE SUMMARY

The Plains CO_2 Reduction (PCOR) Partnership is one of seven regional partnerships formed as part of the U.S. Department of Energy's National Energy Technology Laboratory Regional Carbon Sequestration Partnerships (RCSP) Initiative. The RCSP Initiative is focused on the safe and long-term storage of CO_2 to support the commercial deployment of carbon capture and storage (CCS). To that end, the PCOR Partnership has spent over 10 years developing, testing, and validating the best methods and technologies to conduct the geologic storage of CO_2 (hereafter referred to as CO_2 storage). Through this effort, the PCOR Partnership has formalized an adaptive management approach (AMA) for the commercial development of CO_2 storage projects (Figure ES-1). The use of this approach, which draws upon the collective experience and lessons learned from the PCOR Partnership, represents best practice for advancing CO_2 storage projects toward commercial deployment.

At the heart of the AMA are four technical elements necessary for any successful CO_2 storage project: 1) site characterization; 2) modeling and simulation; 3) risk assessment; and 4) monitoring, verification, and accounting (MVA) (Figure ES-1). Each of these elements plays a key role in gathering and assessing site-specific data that provide a fundamental understanding of the storage complex and its performance. While each of the four technical elements can provide

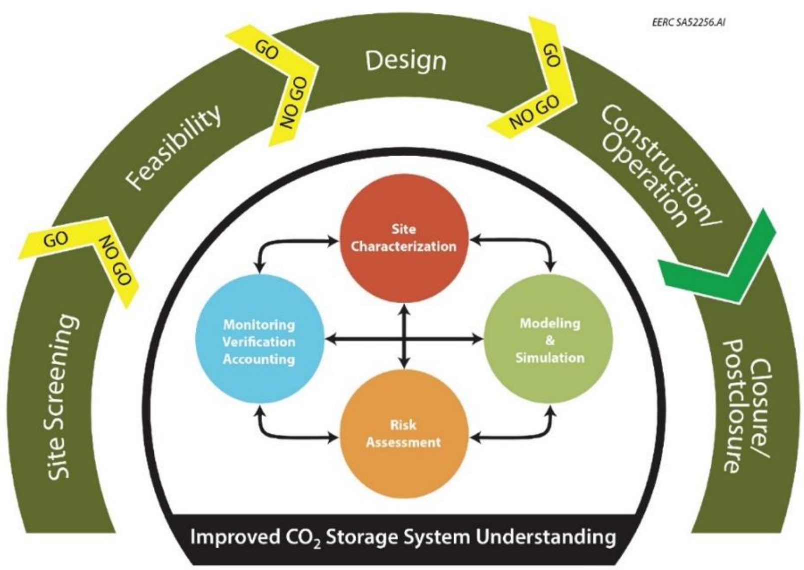

Figure ES-1. The PCOR Partnership's AMA.

useful data independently, integrating them through the AMA yields a streamlined, fit-for-purpose strategy for the commercial deployment of CO_2 storage. Key to this integration and resulting best practice are feedback loops that allow the results of each element to serve as inputs to the others. Each iteration of the AMA creates an improved understanding of the storage complex and thus more targeted and efficient applications of the technical elements. For the purpose of establishing an adaptive management framework, hard lines have been drawn between the technical elements of the AMA. However, in practice, the rapid and seamless interaction between the elements can blur these lines. For example, to aid in the analysis and interpretation of site characterization data, a static geocellular model is often required. While this model development is part of the technical element, modeling and simulation, it is an integral part of the site characterization effort. Likewise, much of the monitoring data collected as part of the MVA technical element can be used to inform site characterization. This back-and-forth flow of data and use of models between the technical elements continues throughout the project.

A CO_2 storage project will advance through a series of life cycle phases—screening, feasibility, design, construction/operation, and closure/postclosure—with the AMA applied during each phase (Figure ES-1). As part of each phase, specific questions, which are guided by technical, economic, and regulatory factors, need to be answered prior to advancing to the next project phase. Following each of the pre-operational development phases of the project (i.e., site screening, feasibility, and design) are go/no-go decision points that allow the project developer to determine if advancement of the project to the next phase is warranted. The AMA provides the necessary framework to gather data needed to answer the questions at each project phase and facilitate commercial deployment; however, the exact boundary or scope of a particular life cycle phase may vary from project to project, with the various phases potentially overlapping one another based on the perspective and needs of the individual project operators.

Currently, CO_2 storage is focused on two primary approaches: 1) dedicated storage in saline formations and depleted oil and gas field and 2) associated storage that occurs primarily during commercial CO_2 enhanced oil recovery (EOR) operations. Although some key differences exist between these approaches, the PCOR Partnership AMA can be used to successfully advance commercial projects in either case. Examples of this versatility have been demonstrated at two of the PCOR Partnership's large-scale (i.e., target injection of 1 million metric tons of CO_2 or more) demonstration projects: the Fort Nelson CCS project and the Bell Creek CO_2 EOR project. The AMA was applied to a dedicated CO_2 storage project in Fort Nelson, British Columbia, with the goal of injecting up to 2 million metric tons of CO_2 per year into a saline formation. The project advanced to the feasibility phase (Figure ES-1), where the first iteration of the technical elements of the AMA (i.e., site characterization, modeling and simulation, and risk assessment) indicated that the original project design posed unacceptable risks to nearby commercial gas production. As a result, the preliminary design of the CO_2 injection scheme (i.e., the location of the CO_2 injection well) was modified. A second iteration of the technical elements of the AMA using the new location of the CO_2 injection well indicated that the risk profile of the project had been successfully reduced to acceptable levels. In addition to the Fort Nelson CCS project, the PCOR Partnership is applying the AMA during the design and operation phases of the ongoing Bell Creek CO_2 EOR project to investigate associated CO_2 storage that occurs during CO_2 EOR. These examples, as well as other work completed by the PCOR Partnership, highlight the successful application of the AMA as a best practice for implementing an integrated, fit-for-purpose approach for the commercial deployment of both dedicated and associated CO_2 storage.

Plains CO_2 Reduction (PCOR) Partnership
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BEST PRACTICE FOR THE COMMERCIAL DEPLOYMENT OF CARBON DIOXIDE GEOLOGIC STORAGE: THE ADAPTIVE MANAGEMENT APPROACH

INTRODUCTION

In 2003, the U.S. Department of Energy (DOE) established the Regional Carbon Sequestration Partnerships (RCSP) Initiative to help develop the technology, infrastructure, and regulations to implement large-scale carbon dioxide (CO_2) storage in the United States. The Plains CO_2 Reduction (PCOR) Partnership, led by the Energy & Environmental Research Center (EERC), is one of the seven partnerships created by this program. The PCOR Partnership is made up of over 120 public and private sector stakeholders and covers an area of over 1.4 million square miles in the central interior of North America, including portions of both Canada and the United States (Figure 1).

Figure 1. PCOR Partnership region.

The RCSP Initiative has taken a phased approach to move toward the commercialization of carbon capture and storage (CCS), which includes both 1) dedicated CO_2 storage in saline formations and depleted oil and gas fields and 2) storage associated with CO_2 enhanced oil recovery (EOR) in producing oil fields. The PCOR Partnership, now in the third phase of its program, has made significant progress in demonstrating the permanent, safe, and practical geologic storage of CO_2 (hereafter referred to as "CO_2 storage"):

- In Phase I of the program (2003–2005), work focused on characterizing the more than 900 major stationary sources of CO_2 as well as the geologic reservoirs suitable for CO_2 storage in the PCOR Partnership region.
- In Phase II (2005–2009), the PCOR Partnership completed four small-scale CO_2 storage field validation tests.
- The multifaceted Phase III program, planned through December 2018, focuses on large-scale demonstration projects and collaboration at the local, regional, and cross-border levels.

BEST PRACTICES MANUALS

DOE has established a process whereby information is conveyed to CCS/carbon capture, utilization, and storage (CCUS) stakeholders using best practices manuals (BPMs). These documents provide specific information and lessons learned regarding key aspects of the characterization, development, and implementation phases of large-scale CO_2 storage projects.

Following this process, the PCOR Partnership is producing a series of BPMs to support the commercialization of CO_2 storage. A "best practice" is a systematic process that has been proven to perform exceptionally well in achieving a specific objective and that can be recommended for use by others in similar situations (Virginia Information Technologies Agency, 2015). The development of a best practice requires the execution of multiple projects where the lessons learned (i.e., knowledge gained through real-world experience and/or modeling and simulation) are identified and evaluated to determine the most effective practices. Consistent with this description, the PCOR Partnership BPMs are based on the lessons learned through the design and implementation of multiple CO_2 storage demonstration projects conducted by the partnership over the past 10 years. These BPMs are being developed to facilitate the technical transfer of the experience gained by the PCOR Partnership to technical and regulatory stakeholders who can benefit from this knowledge.

The PCOR Partnership is creating several BPMs focused on the primary technical elements of a CO_2 storage project, namely, site characterization; modeling and simulation; risk assessment; and monitoring, verification, and accounting (MVA). In addition to advancing the state of the science and understanding of each of these technical elements, the PCOR Partnership has formalized an adaptive management approach (AMA), the use of which represents a best practice for integrating these elements into a fit-for-purpose approach for the commercial deployment of CO_2 storage. A fit-for-purpose approach ensures that the specific activities performed as part of each technical element and the level of detail of those activities are focused on providing the knowledge necessary to make the required management decisions. Using the AMA provides the freedom to tailor each of the technical elements for each CO_2 storage project, thereby avoiding the use of prescriptive approaches that can either result in critical site-specific data gaps and/or the generation of superfluous data not required to make the necessary site-specific technical or regulatory project decisions. Both of these outcomes can adversely affect CO_2 storage projects, the former having the potential to result in operational problems that could lead to the termination of the project and the latter increasing costs unnecessarily.

This BPM describes the concepts and application of the PCOR Partnership AMA. It presents a current snapshot of this integrated approach, which, in keeping with the adaptive management concept, will evolve over time as more lessons learned are compiled during the commercialization of the CO_2 storage industry. The CO_2 storage technical terms used in this document are in general agreement with the definitions of CSA Group Standard Z741-12, a joint Canadian–U.S. initiative published in 2012. One notable exception is Site Characterization (see Section 4.2.1).

BACKGROUND – THE ADAPTIVE MANAGEMENT PROCESS

Adaptive management is a structured, iterative, decision-making process, with the goal of reducing uncertainty over time via system monitoring and adjustment (Figure 2). This adaptive management cycle, which can be traced back to concepts of scientific management pioneered in the early 1900s, starts with a system assessment founded on current knowledge (Williams and others, 2007). Based on that assessment, a system design can be completed and implemented. Monitoring of the system during implementation provides data to evaluate performance against design expectations and, if necessary, leads to adjustments. A reassessment of the system, including potential modifications to the original design, is then performed, and the cycle is repeated until the comparison between system performance and design expectations is within acceptable limits established by the management team and no further adjustments are necessary.

Key features embodied in the adaptive management process include:

- Iterative decision-making, which involves evaluating results and adjusting actions based on lessons learned.

- Feedback between monitoring and decisions, i.e., incorporation of learnings.

- Characterization of system uncertainty.

- Embracing risk and uncertainty as a means of building an understanding of the system.

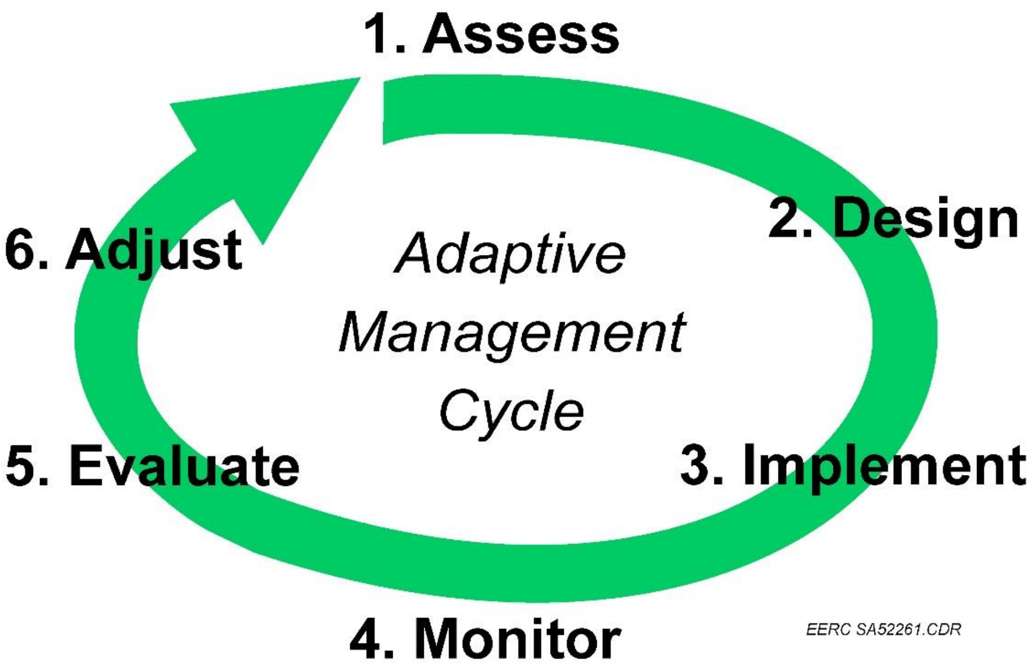

Figure 2. Generic adaptive management process (Williams and others, 2007).

This type of approach can be particularly useful when dealing with complex systems, such as those that exist within a CO_2 storage project, where achieving total knowledge of the system is not possible. Implementation of a CO_2 storage project requires proceeding in a systematic and structured manner, consistent with the scientific method of hypothesis formulation and testing, with the flexibility to make real-time changes based on the collection and analysis of new data. The challenge in using an AMA is finding the appropriate balance between gaining knowledge to improve future management decisions and simultaneously achieving the best short-term outcome based on the current state of knowledge (Allan and Stankey, 2009).

In summary, the adaptive management process involves 1) using available knowledge to select the best strategy to implement a project, 2) presenting the foundational assumptions behind that strategy, and 3) collecting monitoring data to determine if those assumptions hold true. Critical to the process is the ability to adapt or adjust the project in real time to respond to new information obtained through monitoring and other project experience. Given the early stages of the commercial CO_2 storage industry and the general lack of ongoing and completed large-scale storage projects, it is crucial that both successes and failures be documented to provide lessons learned, in turn leading to the development of best practices for the management of future CO_2 storage projects.

AN ADAPTIVE MANAGEMENT APPROACH FOR CO_2 STORAGE PROJECTS

The purpose of this BPM is to present the AMA formalized by the PCOR Partnership as a best practice for employing a fit-for-purpose approach for the commercial development of CO_2 storage projects (Gorecki and others, 2012; Sorensen and others, 2014a, b).

The architecture of the AMA for CO_2 storage projects is shown in Figure 3, with the overall approach building upon the generic adaptive management cycle presented in Figure 2. The AMA consists of four technical elements (i.e., site characterization, modeling and simulation, risk assessment, and MVA). Specific technical activities within these elements are conducted with varying levels of rigor during each of the phases of commercial project development, i.e., site screening, feasibility study, design, construction/operation, and closure/postclosure. As shown in Figure 3, multiple go/no-go decision points exist along the commercial development pathway of a CO_2 storage project. These important junctures allow the developer to assess the current state of the project to determine if it should continue to the next phase.

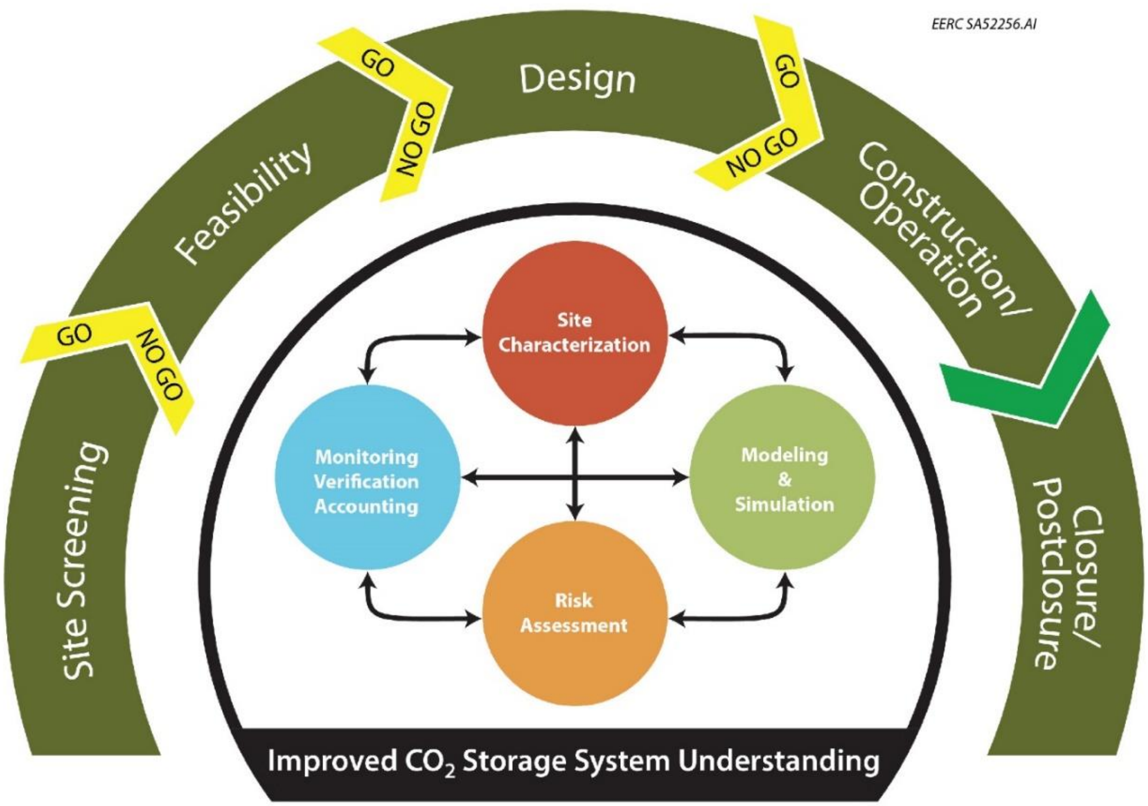

Figure 3. PCOR Partnership AMA for commercial development of CO_2 storage projects (modified from Gorecki and others, 2012). The AMA consists of four primary technical elements (i.e., site characterization, modeling and simulation, risk assessment, and MVA) which are performed at each of the phases of a commercial CO_2 storage project (i.e., site screening, feasibility, design, construction/operation, and closure/postclosure).

The PCOR Partnership developed the AMA (Figure 3) over the course of RCSP Initiative activities, including two field demonstration projects where the AMA was applied to dedicated CO_2 storage in a saline formation (Fort Nelson, British, Columbia) and associated CO_2 storage at an oil field undergoing CO_2 EOR (the Bell Creek Field located in Montana). The details of each of these applications are described in the case studies section of this BPM. The AMA typically begins with some form of site characterization, proceeding in an iterative fashion through modeling and simulation, risk assessment, and MVA. Integral to the approach is a number of feedback loops, which permit the knowledge gained from each element to improve the overall understanding of the storage project, in turn informing the continued application of the other technical elements of the AMA. For example, knowledge gained through the MVA program may improve the static geologic model on which simulation and/or risk assessment predictions are partly based.

An important component of the AMA's successful use throughout PCOR Partnership activities is that it ensures a fit-for-purpose approach – that is, resources are focused on finding cost-effective solutions for key site-specific questions or issues. This approach recognizes that not all of the technical elements in Figure 3 may be required at every project phase and that the level of detail to which they are performed during each phase can vary. Figure 4 provides a generalized depiction of the estimated relative proportion of effort expended on each of the technical elements during each phase of a CO_2 storage project. Site characterization, a primary technical element during the site-screening and feasibility phases of a project, decreases substantially throughout the

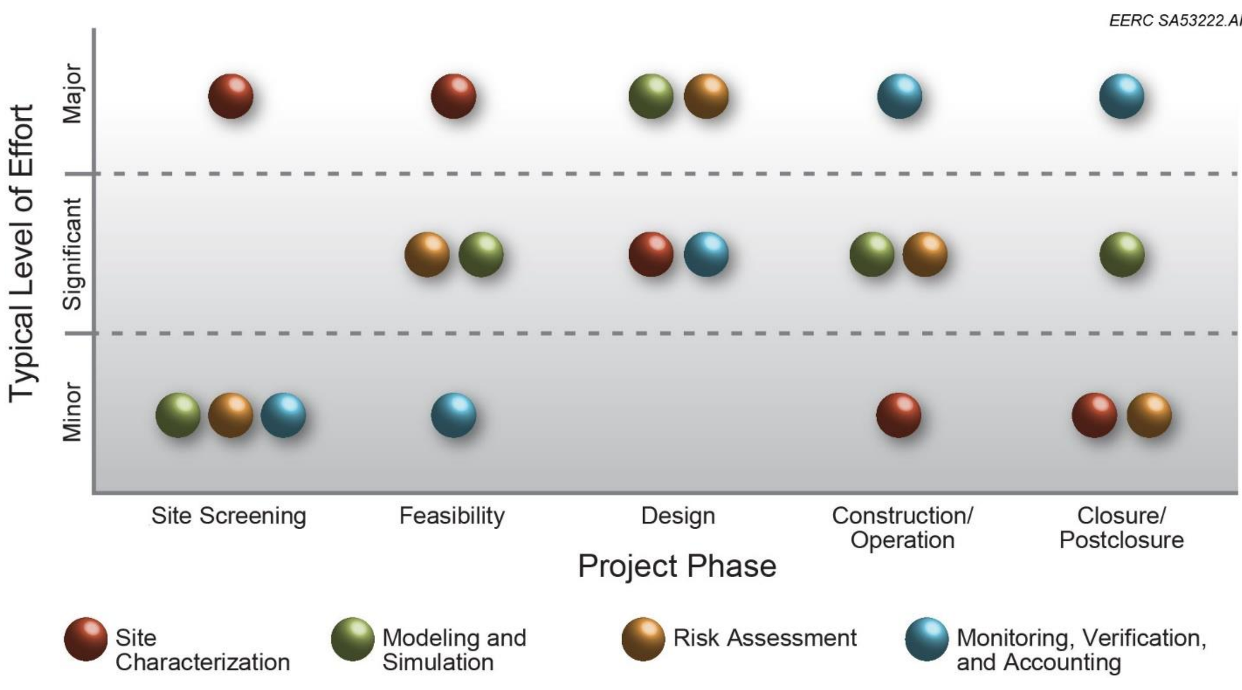

Figure 4. Estimated relative proportion of AMA technical elements performed during each of the project phases of a commercial CO_2 storage project.

design, construction/operation, and closure/postclosure project phases, where it is largely limited to targeted investigations to better understand any unacceptable risks or monitoring anomalies that might arise. At the same time, risk assessment and MVA elements are initiated during the feasibility phase, increasing steadily and eventually becoming the focus of the technical activities in the construction/operation and closure/postclosure phases of the project. Lastly, modeling and simulation are present in all project phases, with the bulk of the efforts focused on the feasibility, design, and construction/operation project phases.

Consistent with its fit-for-purpose philosophy, the AMA is driven by the nature of the questions addressed at each phase of a CO_2 storage project and the level of information needed by the project developers to make go/no-go decisions at critical points in the commercialization of the project. It should be noted that the technical elements applied during each project phase are also influenced by the nature of the storage scenario, e.g., dedicated or associated. This AMA BPM focuses on the commercial deployment of dedicated storage projects; however, a discussion highlighting key differences in the AMA when applied to an associated storage project is included later in this BPM.

Phases of a CO_2 Storage Project

The project phases associated with the commercial development of a CO_2 storage project include site screening, feasibility, design, construction/operation, and closure/postclosure (Figure 3). The goal of the AMA is to apply and integrate the four primary technical elements identified in Figure 3 to meet the technical, economic, and regulatory needs of each phase. This approach ensures that activities are conducted in a cost-effective manner during each phase to provide answers to the critical questions necessary to successfully implement the project at a commercial scale. A more detailed description of the phases of a commercial CO_2 storage project is presented below; however, it should be noted that the exact boundary or scope of a particular life cycle phase might vary from project to project, with the various phases potentially overlapping one another based on the perspective and needs of the individual project operators.

Site Screening

The goal of site screening is to identify one or more candidate storage sites that 1) are economically accessible to a source of CO_2, 2) have sufficient capacity and injectivity to store supplied CO_2 at the required rate, and 3) have the geologic structure or stratigraphy necessary to securely contain the CO_2 in the storage reservoir. Detailed site-screening criteria can be developed on a project-specific basis or adopted from generic guidelines (e.g., IEA Greenhouse Gas R&D Programme, 2009).

Key questions to be answered during the site-screening phase include:

- Are there candidate storage sites within an economical distance from the source[1] that have the geologic conditions required to inject, store, and securely contain the target quantities of CO_2?

[1] Preceding site screening for all CO_2 storage projects is the "Project Definition," which defines a set of technical, economic, and social criteria that are used to guide the development of the project. This effort defines the overarching

- Are there land or subsurface access issues or other uses of the subsurface in proximity to the storage sites (e.g., commercial oil and gas production) that may interfere with the ability to store CO_2?

- What agency or agencies have regulatory authority over the project, and are there any regulatory hurdles that may preclude moving forward with the project at any of the candidate sites?

The candidate storage sites selected for further analysis will proceed to the next project phase: feasibility study. In the event that no candidate sites are identified during site screening, a no-go decision by the project operator would be warranted.

Feasibility Study

The feasibility study will determine the technical and economic strengths and weaknesses of storing CO_2 at the candidate geologic storage sites identified during site screening to assess their potential to serve as the location for a commercial CO_2 storage project. During this phase, a conceptual design of the storage system will be developed, including transportation of the captured CO_2, any necessary surface facilities for CO_2 handling and processing, CO_2 injection, and a surface and subsurface-monitoring program. To develop the conceptual design and complete the feasibility study, the following types of questions will need to be answered:

- Are sufficient data available to adequately characterize the storage site or will acquisition of new data through exploratory fieldwork be required?

- What combination of strata will be defined as the storage complex? This may consist of a single reservoir and overlying seal or multiple reservoir and seal layers.

- How many CO_2 injection wells will likely be necessary to inject the expected quantity of CO_2 at the rate it will be delivered to the site? Where should these wells be placed and to what depth?

- What surface infrastructure will be necessary to transport and process the CO_2 prior to injection (e.g., size and length of pipeline, CO_2 cleanup needs, compression needs, etc.)?

- What is the overall footprint of the storage complex, including the area of review (AOR)[2]?

- Is it necessary to secure pore space from affected property owners and/or negotiate landowner agreements to gain access to portions of the storage site?

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project constraints that must be met throughout the implementation of the project phases and includes such information as the quantity of CO_2 that must be stored and the maximum distance it can be economically transported. This BPM assumes that this effort has been completed for a CO_2 storage project prior to implementing the AMA.

[2] The AOR is the surface area within which potential adverse effects may occur as a result of CO_2 plume migration and/or pressure elevation. The purpose of the AOR is to assist the regulator and all stakeholders in assuring that the storage risks are being appropriately managed (Alberta Energy, 2013).

- What are the applicable state and/or federal regulations and permitting requirements for the construction and operation of the storage system, including MVA? What data are needed to meet these regulatory and permitting requirements? Who is liable for the stored CO_2 following the cessation of active CO_2 injection?

- What potential environmental risks may exist at the site, e.g., potential leakage through legacy wellbores? Is there a potential to impact sensitive environmental receptors?

- What is the overall estimated cost of the project, including any additional site characterization activities (e.g., seismic surveys, additional exploration wells, etc.) required to finalize the facility design or secure permits required for construction and operation?

At the conclusion of the feasibility study, a storage site, or sites, will be selected for the CO_2 storage project.[3] The preliminary economics of the project will be estimated, along with an assessment of the project-specific risks, which include both technical and nontechnical risks to the project developer as well as the public at large and other stakeholders. This type of cost/benefit information will likely be required by management to make project-funding decisions. It is important to note that while a large amount of work will be performed during the feasibility phase, there may still be significant uncertainty associated with the results. For example, feasibility study cost estimates for environmental remediation projects, which often involve active subsurface injection of liquid and/or gas, can be on the order of −50% to +100% (U.S. Environmental Protection Agency, 2000). This potential level of uncertainty should be factored into the decision-making process when a CO_2 storage project is planned.

Design

Following storage site(s) selection, a detailed design of the storage system will be developed based on the conceptual design created during the feasibility phase. The detailed design will include all necessary information for the preparation of the final project cost estimate, permitting, and construction of the facility. At this project phase, the estimates of the project economics will improve and may be on the order of −10% to +15% (U.S. Environmental Protection Agency, 2000). A reasonable time line for permit submissions and approvals should also be developed at this time, along with a construction schedule for the installation of wells and surface infrastructure.

Storage projects will typically need to assess a wider geographical area than the anticipated areal extent (footprint) of the plume of injected CO_2. For example, in U.S. jurisdictions, a critical component of the final project design is the formal definition of the AOR for the storage system. The AOR establishes the lateral extent of CO_2 plume migration and subsurface pressure elevation impacts expected from the injection and storage of the CO_2. The AOR delineates the boundaries of the storage system that must be managed and monitored during the subsurface injection of the CO_2 to ensure that no adverse effects result from this action. The formal requirements for defining an AOR vary by regulatory jurisdiction across the PCOR Partnerhip region, although in the United

[3] There may be circumstances where more than one site will qualify as an acceptable storage site and will be required to store the desired quantities of CO_2.

States, the U.S. Environmental Protection Agency (EPA) has codified its definition in its Class VI Geologic Storage Well Regulations (U.S. Environmental Protection Agency, 2010a). To comply with the EPA requirements, the AOR is usually determined using computational models to ensure that it includes the full extent of the anticipated plume migration and significant pressure propagation as defined by applicable regulations, encompassing all surface and subsurface areas.[4] While initial estimates of the AOR will be made during the feasibility phase of the project, the design phase will produce the definition serving as the basis for the final design of the CO_2 injection scheme and MVA program as well as the acquisition of required lease agreements and permits.

In addition to finalizing the AOR during the design phase, other important questions that will be addressed include:

- What are the detailed requirements of the surface infrastructure that is needed, and what are the costs to deploy and operate the surface infrastructure?
- How many CO_2 injectors are needed? Where should they be placed, and how must they be constructed?
- What are the specific elements of the MVA plan necessary to meet the operating and regulatory permitting requirements?
- What type of surface and subsurface measurements are needed to implement the MVA program? Where should monitoring instrumentation be placed, and how often should the monitoring data be collected and analyzed?
- Are deep monitoring wells required to meet the MVA program requirements? If so, how should they be constructed and where should they be placed?
- What are the costs to deploy and operate the MVA technologies?
- What are the major areas of technical risk associated with the storage operations, and can they be managed within acceptable risk limits?

It should be noted that many of the above questions are similar to those asked and answered as part of the feasibility study. What is different during this phase of project development are the quantity and quality of data that are now available to provide answers to these questions, usually provided by additional fieldwork activities conducted during the design phase. Compared to the feasibility study, the answers at this phase of the project can be provided with more certainty and provide a more definitive basis for making the final go/no-go decision before approval of capital expenditures.

[4] Generally, regulations define "significant pressure propagation" as an elevation of pressure to a level capable of moving a column of brine upward to the nearest underground source of drinking water (USDW).

Construction/Operation

Following a final decision to proceed with the project, the construction/operation phase of the project will be initiated. Construction activities for associated storage projects may be less significant than those of dedicated storage projects, as much of the infrastructure may already be present for the former because of primary (and, in some cases, secondary) oil recovery operations at the site. It should be noted that monitoring to establish baseline conditions pertinent to the MVA program would normally be collected before or during the construction phase.

Operations will be focused on the safe injection of the CO_2 into the storage reservoir(s) and the monitoring of the storage complex and extended surface and subsurface environments within the AOR. The purpose of monitoring is to document system performance and demonstrate the absence of unacceptable impacts to environmental or other receptors. Questions to be answered during this phase include:

- Is the injected CO_2 securely contained within the storage complex and behaving in conformance with model predictions?

- Have any unexpected operational issues been observed, e.g., unusual pressure buildup?

- Has the project risk profile changed based on field observations and the monitoring data that are collected?

Several of the same questions asked during the feasibility and design phases may be addressed again during this phase of the project. The key difference is that operational and routine MVA data and observations are now available, providing a better understanding of storage performance.

One of the unique challenges in implementing the technical elements of the AMA during the operational phase of a project is the timeliness of the feedback loop between MVA and the other technical elements. For example, the value of conducting large time-lapse seismic surveys as part of the MVA program may be limited during this project phase since the collection, processing, and interpretation of the seismic data often take several months. During that period of time, CO_2 injection into the subsurface continues to occur and any subsurface operational issues associated with that injection may go undetected. To address this conundrum, complementary monitoring activities should be planned, e.g., seismic surveys accompanied by downhole pressure measurements, to provide a more real-time assessment of subsurface conditions. Alternatively, new and innovative monitoring techniques capable of collecting MVA data in real time are needed. This monitoring technology gap represents an area for additional research and development.

Closure/Postclosure

Closure/postclosure is the last phase of a CO_2 storage project and is driven by regulatory requirements and issues associated with the long-term liability of the injected CO_2. Closure involves the actual cessation of CO_2 injection operations and the decommissioning of the storage facility, including plugging of wells and removal of surface operating facilities and infrastructure.

At the time of closure, it is necessary to demonstrate that the stored CO_2 is securely contained within the storage complex.

Postclosure is a period following closure that extends for a period of time detailed in the permit. In the United States, current EPA regulations have established a postclosure period of 50 years for monitoring following the cessation of injection; however, the final rule provides some flexibility regarding the duration of this period by allowing the EPA director to decrease or increase it based on site-specific data (U.S. Environmental Protection Agency, 2010a). During postclosure, it is necessary to document that the stored CO_2 is securely contained in the storage complex and that there is no discernible leakage or evidence of environmental impacts from CO_2 or other formation fluids

Questions to be answered during this final phase of the project include:

- What level of information is needed to assure regulatory agencies that the CO_2 has been safely stored at the time of closure and will remain in the storage complex during the postclosure period?

- Is the risk profile of the site remaining at acceptable levels? What mitigation actions should be taken if risk levels are exceeded?

- How frequently should the site risk profile be updated during the postclosure period?

Following closure and postclosure, project developers will have met their obligations, and no additional site activities are required.

Cost Considerations

An important consideration that deserves attention is the cost associated with implementing the various project phases. Figure 5 illustrates the potential range of total costs for each project phase. Similar to the type and level of technical activities performed, the total cost of each project phase will be site-specific and can be expected to vary considerably as a result of many factors, including scale, scope, current regulatory requirements, and project type (i.e., dedicated versus associated storage). For example, the scale of a project can affect the level of initial site characterization activities performed, the type and extent of required infrastructure, and the overall operating costs of the project. Additional variables to consider when estimating cost for each phase include:

- The existing knowledge base for all aspects of the prospective project (e.g., Have site characterization activities already been completed? Have the requirements of applicable federal, state, and local regulations been defined?).

- The desired level of certainty required to move from one phase of the project to the next (e.g., Will it be necessary to drill additional characterization wells or collect more seismic data?).

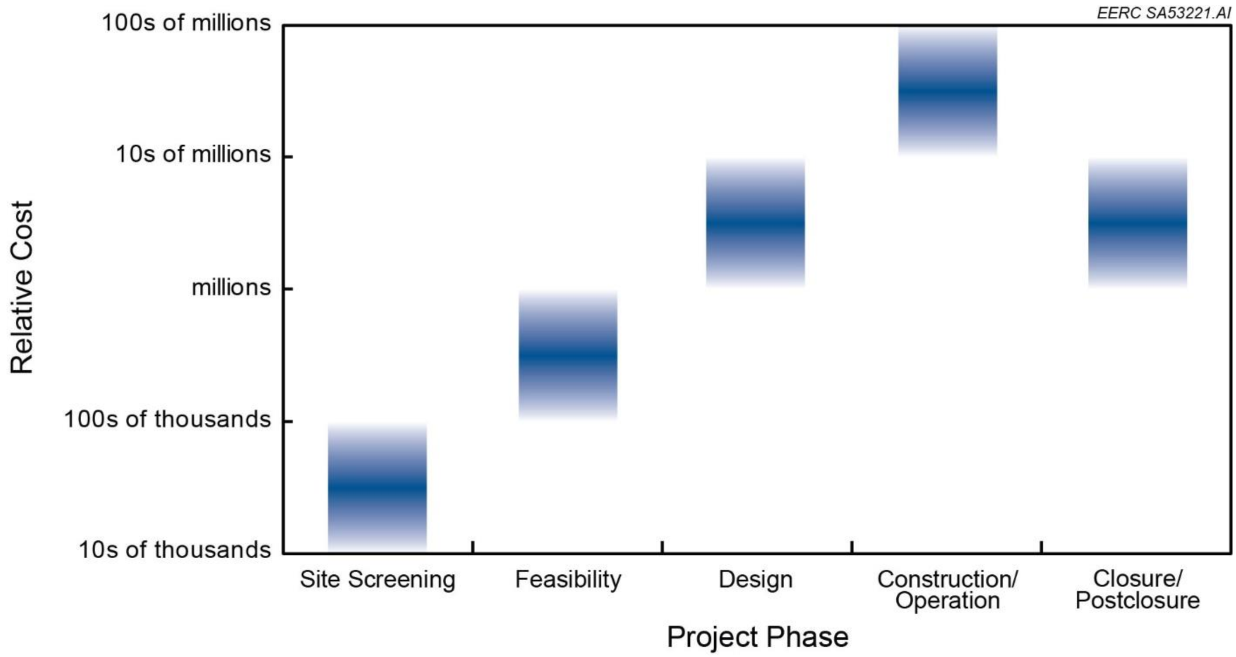

Figure 5. Potential range of approximate total cost for each phase of a CO_2 storage project.

- The level of additional infrastructure investment required (e.g., Are there existing pipelines or injection/monitoring wells?).

Because of the limited number of active and completed CO_2 storage projects, the limited availability of cost data from those projects, and numerous site-specific considerations, the costs for each project phase cannot be specified for a generic CO_2 storage project beyond the generalized, relative ranges presented in Figure 5.

Technical Elements of the AMA

Descriptions of the key technical elements of the AMA (Figure 3) are provided below. Also discussed below is the relative importance of each element to the various phases of a CO_2 storage project as described above. Figure 4 illustrates how the focus of the technical elements shifts over time as a project moves through the various phases of commercial development. It should be noted that for the purpose of establishing an adaptive management framework, hard lines have been drawn between the technical elements of the AMA. However, in practice, the rapid and seamless interaction between the elements can blur these lines. For example, to aid in the analysis and interpretation of site characterization data, a static geocellular model is often required. While this model development is part of the technical element, modeling and simulation, it is an integral part of the site characterization effort. Likewise, much of the monitoring data collected as part of the MVA technical element can be used to inform site characterization. This back-and-forth flow of data and models between the technical elements continues throughout the project, with the AMA ensuring that their integration is fit-for-purpose and provides the answers to the critical questions associated with each phase of a commercial project. More in-depth discussions of each of the AMA technical elements will be presented in future PCOR Partnership BPMs dedicated to each of those elements.

Site Characterization

Site characterization activities include the acquisition and analysis of data (e.g., installation of wells, collection of seismic data, etc.) to develop an understanding of the site-specific properties and characteristics of the surface and subsurface environments. Depending on the project phase, several different types of data may be collected, including petrophysical, mineralogical, geomechanical, hydrogeological, geochemical, and others (e.g., well logs). As shown in Figure 4, data acquisition occurs throughout the entire project, although the intensity of the effort and the characterization techniques employed vary with the different phases of the project. For example, reliance on readily available information in published literature and from state regulatory agencies will dominate the site screening and early stages of the feasibility phases of most projects; however, field data collection activities will eventually dominate the efforts of the feasibility phase and into the project design and construction/operation phases of the project. Reduced, but targeted, field efforts during operations are primarily focused on addressing unacceptable risks and/or monitoring anomalies. Site characterization is not typically conducted during the closure/postclosure phase of the project, but may be required to investigate any unacceptable risks and to define mitigation actions, should they be required.

Modeling and Simulation

Static geocellular models that represent the subsurface, as well as dynamic simulations to predict the effects of injecting and storing CO_2, are important for the design of a CO_2 storage system, an assessment of the project risks, and the design and interpretation of the results of an MVA program. A primary challenge associated with this element is balancing the complexity and detail of a geocellular model with the computing power and time needed to generate predictions based on that model. Modeling efforts typically begin early in the development of a project and continue throughout the operation of the site, with the precision and complexity increasing over time. For example, preliminary static models with little or no dynamic simulation are often sufficient to meet the needs of the screening phase of the project. However, as the project moves through feasibility toward a final design, running CO_2 injection simulations becomes critical in defining the AOR as well as in developing a better understanding of potential risks related to CO_2 migration and subsurface pressure effects. If field production or injection data exist prior to the start of CO_2 injection, as is often the case for CO_2 EOR or depleted field sites, then simulation models can be history-matched to improve predictions of reservoir performance. Because of the inherent uncertainties in the data that are used to create the static and dynamic models, they should be frequently assessed and, if necessary, revised as operating and MVA data are gathered during the operations phase of the project to allow history matching at regular intervals. Moving into the closure/postclosure phase of a project, the resulting calibrated models should be sufficient to continue to support the interpretation of MVA data that are collected.

Risk Assessment

The identification and assessment (qualitatively or quantitatively) of the potential risks that threaten the success of a CO_2 storage project occur early in the development of a project and are refined over time as more characterization, operational, and monitoring data become available. While a high-level risk assessment may be performed at the site-screening phase using generic lists of risks associated with the geologic storage of CO_2,[5] initial risk assessments are usually conducted during the feasibility phase of the project to create a site-specific risk register which can be updated during subsequent phases of the project based on refined predictions of the system performance. Risk assessments conducted at the design phase of the project are especially important since it is still relatively easy to make changes in the storage system configuration and planned operations to eliminate potentially unacceptable risks. Conducting risk assessments will continue through the operation and closure/postclosure phases of the project based on data collected through the MVA program. Continuation of these efforts in the latter phases of the project is important to demonstrate to the public, federal and state regulators, and other stakeholders that the risk profile of the subsurface storage of CO_2 is being continuously monitored and remains at an acceptable level.

Monitoring, Verification, and Accounting

MVA activities are required for all CO_2 storage projects to track the migration of injected CO_2 as well as to confirm that the surface and subsurface environments are not negatively impacted by injection activities. There are multiple uses for MVA data, with the primary goal of verifying that the injected CO_2 and other formation fluids are contained within the target storage complex. In addition, regulatory requirements governing the storage system may require measurement of the total mass of CO_2 that is injected into the subsurface. These monitoring data also provide valuable information to support the other technical elements of the AMA such as the continued refinement of models and simulations and the site-specific risk assessment.

Other than baseline monitoring activities, which may be performed during the feasibility, design, or construction/operation phases of the project, MVA activities are primarily implemented during operations and will continue through closure/postclosure. There are many technologies, including surface, near-surface, and deep subsurface monitoring techniques, which will be employed as part of the MVA activities at a CO_2 storage site. Many of these techniques, e.g., geophysical logging and seismic surveys, are identical to those used during site characterization activities; however, the use of the data is different. During site characterization activities, the data are used to gather new information and/or verify existing data related to the static geologic storage system prior to CO_2 injection. In contrast, their purpose as part of the MVA program is to monitor the dynamic response of the system during active CO_2 injection and to document the containment of the CO_2 in the storage complex during operation and through the closure/postclosure period.

For the purpose of establishing an adaptive management framework, hard lines have been drawn between the technical elements of the AMA. However, in practice, the rapid and seamless interaction between the elements can blur these lines. For example, to aid in the analysis and

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[5] The Features, Events, and Processes (FEP) database developed by Quintessa provides a good example of the generic risks typically associated with CO_2 storage (Quintessa, 2013).

interpretation of site characterization data, a static geocellular model is often required. While this model development is part of the technical element, modeling and simulation, it is an integral part of the site characterization effort. Likewise, much of the monitoring data collected as part of the MVA technical element can be used to inform site characterization. This back-and-forth flow of data and use of models between the technical elements continues throughout the project.

APPLICATIONS OF THE ADAPTIVE MANAGEMENT APPROACH FOR CO_2 STORAGE PROJECTS

Dedicated Versus Associated Storage

Consistent with the philosophy of the AMA, the fit-for-purpose mix and progression of technical elements that are employed will be different for dedicated and associated storage projects. For example, since the latter will typically involve an oil field that has been active for some time, there will likely be fewer requirements for acquisition of data through new fieldwork activities. At the same time, the documentation of CO_2 stored may be more complex because of the number of injection wells and recycling system, resulting in greater efforts for the technical elements of modeling, simulation, and MVA. A brief discussion of some of the differences in applying each of the technical elements of the AMA for dedicated and associated storage is provided below.

Site Characterization

As is the case for dedicated storage, CO_2 EOR projects will rely heavily on readily available information in literature and other public sources to inform site characterization during the early phases of the project, i.e., site screening and feasibility. However, since oil fields (especially those already undergoing EOR) are usually well characterized, there will likely be significant nonpublic data available for assessment of associated storage. As a result, only limited site characterization field activities, if any, will likely be required during the initial phases of the project. If site characterization activities are performed, they would be to address data gaps focused specifically on the storage aspects of the site as opposed to incremental oil recovery (although the data collected would likely provide a dual benefit to the project).

Modeling and Simulation

Similar modeling and simulation efforts are required for both dedicated and associated storage sites since these activities are focused on the prediction of the migration of the injected CO_2 in the subsurface. In the case of associated storage, additional objectives focused on CO_2 EOR operations may exist (e.g., estimated recoverable oil, effect of oil production on CO_2 plume evolution).

Risk Assessment

Both dedicated and associated storage will result in the long-term subsurface containment of the injected CO_2; however, risk profiles for associated storage projects may differ substantially from dedicated storage. On the one hand, given that reservoirs targeted for CO_2 EOR will likely have considerable existing subsurface characterization and operational data, it is likely that risks associated with reservoir performance and geologic uncertainty are well understood and are at acceptable levels. Conversely, the activities that garnered the existing data (e.g., the installation of numerous CO_2 injection and oil production wells) may increase the likelihood of environmental risks associated with out-of-zone vertical migration of CO_2 into overlying domains of concern (e.g., USDW, surface waters, atmosphere), requiring the implementation of a comprehensive site risk assessment and an extensive MVA programs.

Monitoring, Verification, and Accounting

The goals of the MVA activities for associated storage projects will be identical to those required for dedicated storage projects, focusing on the tracking of the migration of CO_2 in the subsurface and documenting containment in the storage complex. However, major differences in the extent and duration of the MVA requirements may exist because of the potential differences in the risk profiles identified above as well as differences in the regulatory environments in which they operate. For example, it may not be necessary to monitor CO_2 EOR projects in accordance with the recent requirements of EPA for CCS sites (i.e., Subpart RR reporting requirements [U.S. Environmental Protection Agency, 2010b]) or to extend monitoring beyond the period of CO_2 injection, as monitoring may be terminated at the time operations cease. These differences will be largely site-specific in nature and will be driven by the applicable regulatory requirements as well as operating and management decisions made by the site operator.

Case Studies of the PCOR Partnership

As part of the PCOR Partnership Program, the AMA has been applied at two field demonstration projects.[6] Specifically, it was employed as part of a feasibility study for the dedicated storage of CO_2 in a deep saline formation in Fort Nelson, British Columbia, as well as the associated storage that occurs during the operation phase of a CO_2 EOR project at the Bell Creek Field in Montana (Figure 6). These case studies not only demonstrate the application of the AMA at two CO_2 storage sites but also highlight some of the key differences in employing it at dedicated and associated storage sites. More detail on these projects and other applications of the AMA can be found in the numerous publications available on the Web site of the PCOR Partnership (www.undeerc.org/pcor/).

Feasibility Study – Dedicated CO_2 Storage in a Saline Formation

Following site screening performed by the project operator, Spectra Energy and Transmission (SET), the PCOR Partnership and SET performed a feasibility study for a dedicated storage project at Fort Nelson in British Columbia, Canada. The goal of the project was to remove CO_2 from the sour shale gas of the Horn River play and transport it approximately 2.2 kilometers for injection into a saline rock formation (Figure 7). The first iteration of the AMA (Figure 8) was

[6] As part of the Phase III activities of the RCSP Initiative, the PCOR Partnership is conducting large-scale CO_2 storage demonstration projects, with a goal of injecting a minimum of 1 million metric tons of CO_2 into the subsurface.

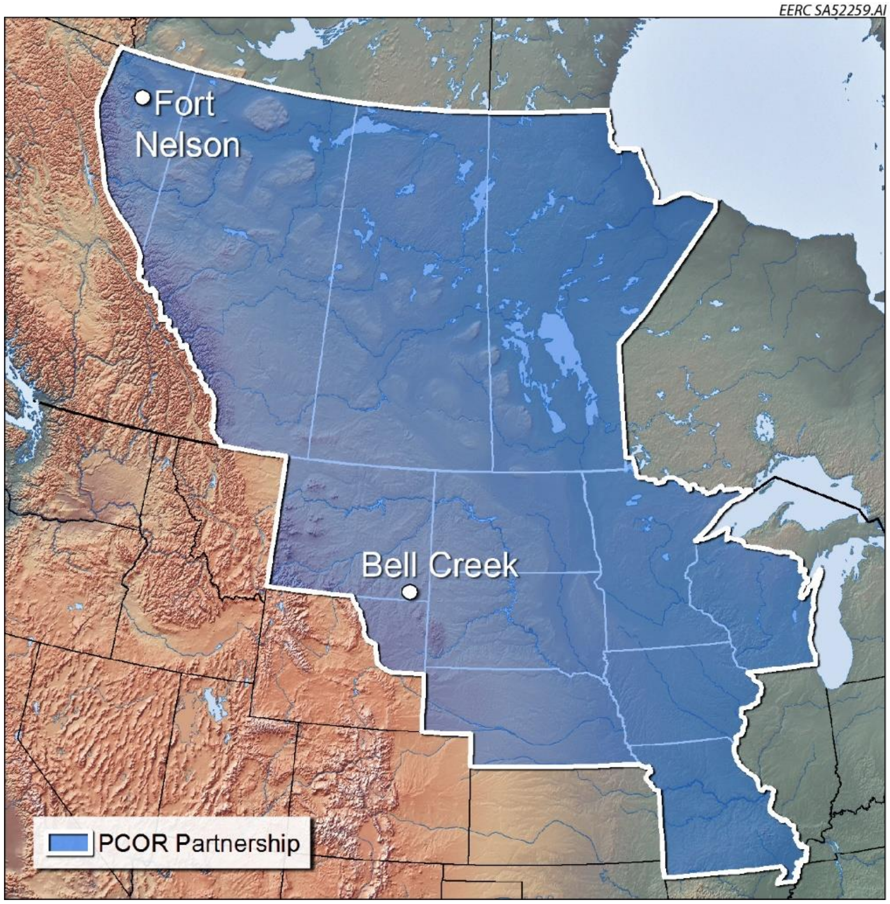

Figure 6. Location of two PCOR Partnership Phase III field projects.

initiated with a site characterization effort that included a literature review and data gathering for known geologic formations within the region of interest to gain a broad-based understanding of the presence of potential storage targets and sealing layers. Existing 2-D and 3-D seismic surveys previously performed in the region were obtained, and all available data were used to characterize the existing subsurface geologic conditions, especially those related to storage reservoir injectivity, capacity, and integrity. Potential injection horizons and well locations were selected based on analysis and interpretation of these data. The gathered data sets served as the basis for static and dynamic modeling activities to provide stakeholders and decision makers with insight regarding the viability of CO_2 storage in the target reservoir. An initial risk assessment was conducted and used to highlight any potentially unacceptable risks and identify additional site characterization needs to address them. Potential MVA technologies were also identified to serve as the primary means by which the risks could be monitored and managed. Figure 8 presents a graphical representation of the first iteration through the AMA during the Fort Nelson feasibility study.

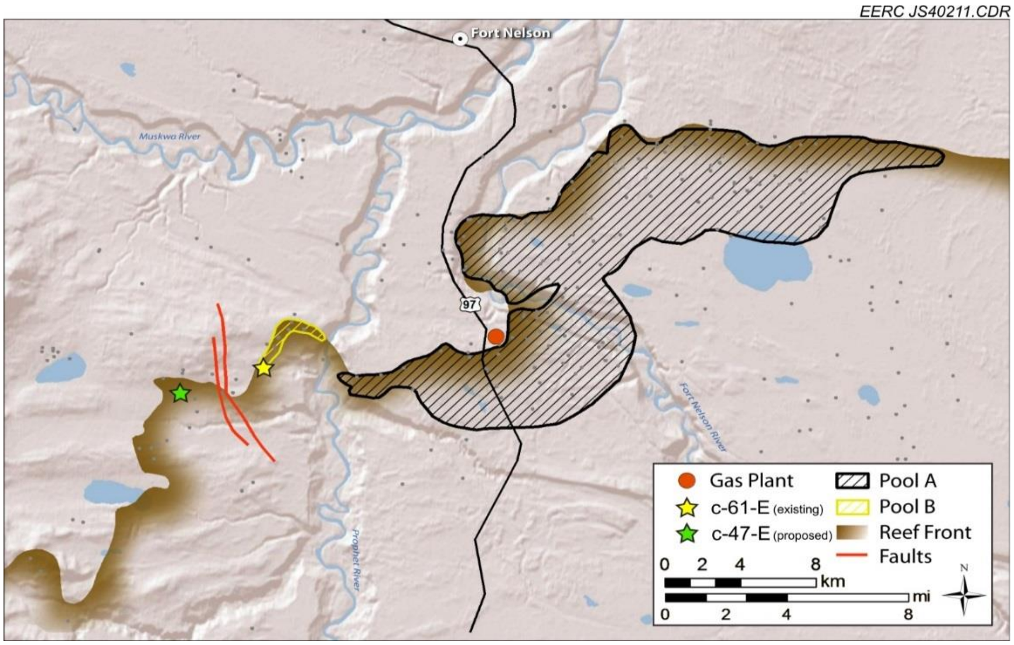

Figure 7. Map showing the location of potential alternative CO_2 injection points (c-47-E and c-61-E) and nearby deposits of natural gas (Pools A and B) investigated as part of the Fort Nelson feasibility study (Sorensen and others, 2014b).

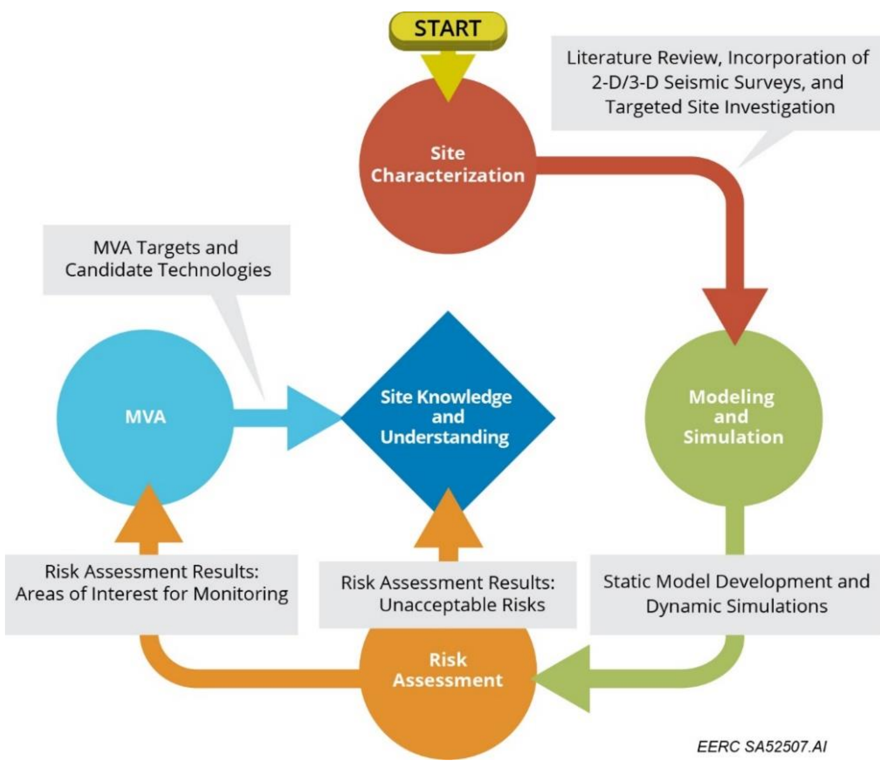

Figure 8. First iteration of the AMA conducted by the PCOR Partnership during the feasibility phase of the Fort Nelson CCS project.

The output of the first iteration of the AMA (Figure 8) indicated that CO_2 injection had the potential to impact nearby gas pools currently under commercial production (Figure 7). SET viewed this as an unacceptable risk, which led to a second iteration of the AMA (Figure 9). This second pass through the technical elements of the AMA included the gathering of additional, targeted site characterization data; the development of revised and improved geomodels and numerical simulations; and the conduct of a second risk assessment. The results of this second iteration of the AMA revealed that by moving the proposed location of the CO_2 injection well approximately 5 kilometers west of the original injection location (i.e., from c-61-E to c-47-E in Figure 7), the overall project risk was reduced to acceptable levels, largely attributable to the decreased likelihood of impacting the nearby gas pools. Over the course of the feasibility study for this project, multiple iterations of site characterization, modeling/simulation, and risk assessment activities occurred, yielding three versions of a reservoir model and two rounds of risk assessment. SET used this information to inform a go/no-go decision ultimately placing the project on hold because of the lack of a viable business case for operating a dedicated CO_2 storage project in British Columbia. Nevertheless, the Fort Nelson CO_2 storage feasibility study represents an excellent example of how the AMA provided a fit-for-purpose approach that helped the project developers gain the information they needed to make an informed go/no-go decision.

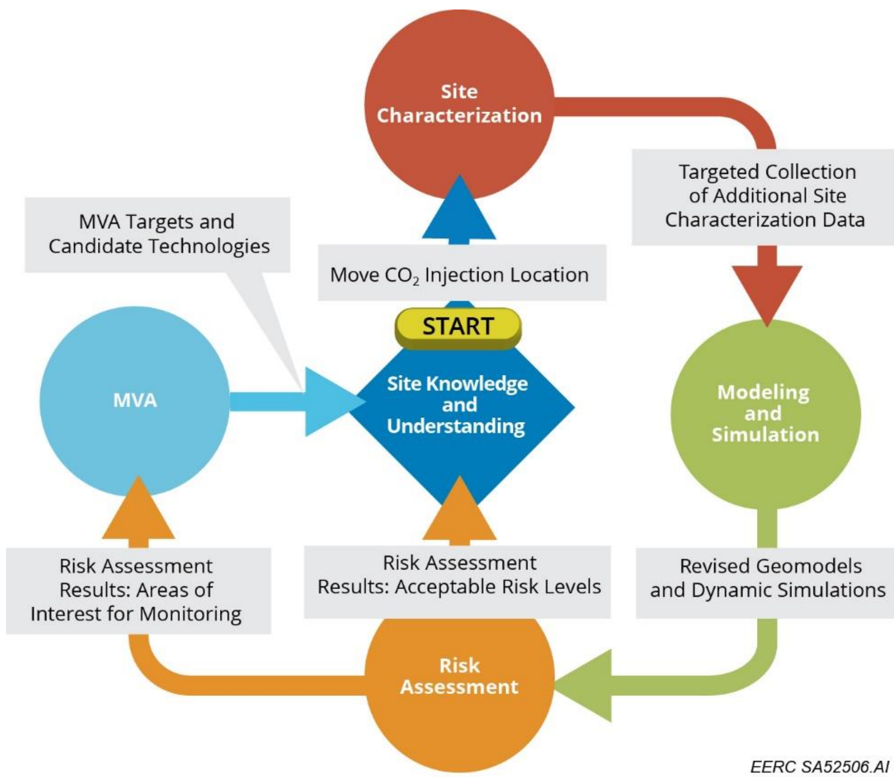

Figure 9. Second iteration of the AMA conducted by the PCOR Partnership during the feasibility phase of the Fort Nelson CCS project.

Operation – Associated CO_2 Storage During CO_2 EOR

The PCOR Partnership is participating in an ongoing field project focused on studying the associated storage of CO_2 during the operation of a commercial CO_2 EOR project led by Denbury Onshore LLC (Denbury) in southeastern Montana. The PCOR Partnership's involvement in this CO_2 EOR project began in 2011, with CO_2 injection at the site beginning in May 2013. CO_2 is transported from the ConocoPhillips Lost Cabin and Exxon Shute Creek gas plants and injected into an oil-bearing sandstone reservoir in the Bell Creek Field for the purposes of CO_2 EOR (Figure 10).

The AMA was applied during the design and construction/operation phases of the project as a supplement to the CO_2 EOR development of the field led by Denbury. The PCOR Partnership's application of the AMA focused on the development of an MVA strategy for documenting the containment of CO_2 in the various phases of the field's staged development as well as quantifying the CO_2 stored. The first iteration of the AMA included targeted site characterization, modeling and simulation, and risk assessment activities to support the development of an MVA strategy, which involved the installation and testing of monitoring technologies for the collection of surface,

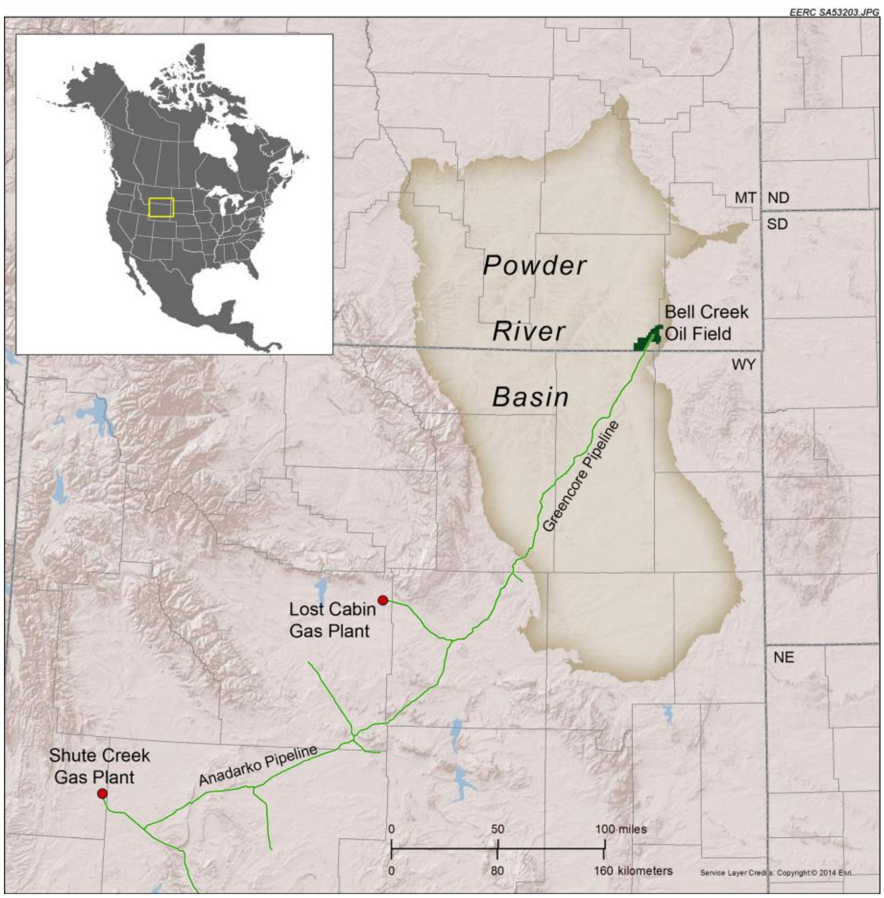

Figure 10. Map depicting the location of the Bell Creek oil field and the pipeline route to the site from the Lost Cabin and Shute Creek gas plants.

near-surface, and deep subsurface monitoring data (Figure 11). Through the feedback loops of the AMA, these initial MVA data provided valuable information for targeting additional site characterization efforts, improving modeling predictions through the validation and history-matching of the geomodels and simulation results, and identifying and assessing geologic and operational variables affecting the performance of the field. For example, operational data collected as part of the MVA program led to the conduct of additional surface seismic surveys to help interpret field observations of the CO_2 EOR operations. These additional seismic data revealed the presence of previously unknown geologic barriers and sand bridges. With an understanding of the presence of these geologic features, modeling and simulations of the site were improved, resulting in better history matches and improved predictions of CO_2 presence and migration in the subsurface. The improved modeling predictions then provided a basis for revising the MVA strategy for the site as well as for conducting another risk assessment, which also helped guide additional MVA decisions (Figure 12). Like Fort Nelson, the Bell Creek project provides a clear demonstration of applying the AMA for a CO_2 storage project. The Bell Creek project also serves to highlight some of the unique elements of applying the AMA for associated storage during CO EOR.

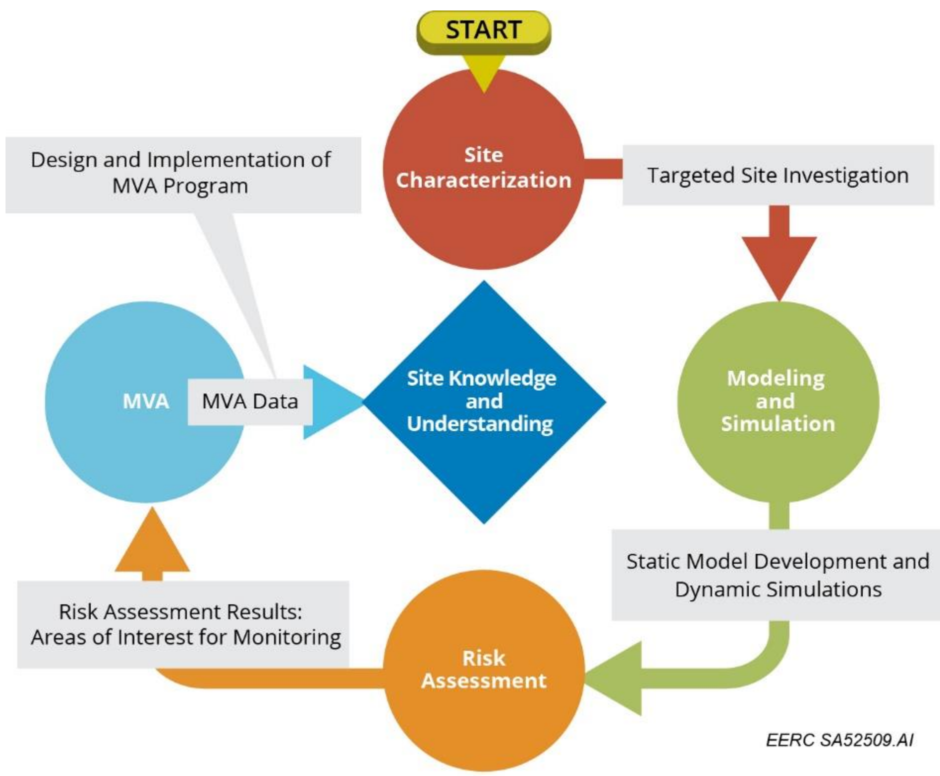

Figure 11. First iteration of the AMA conducted by the PCOR Partnership during the operation phase of the Bell Creek CO_2 EOR project.

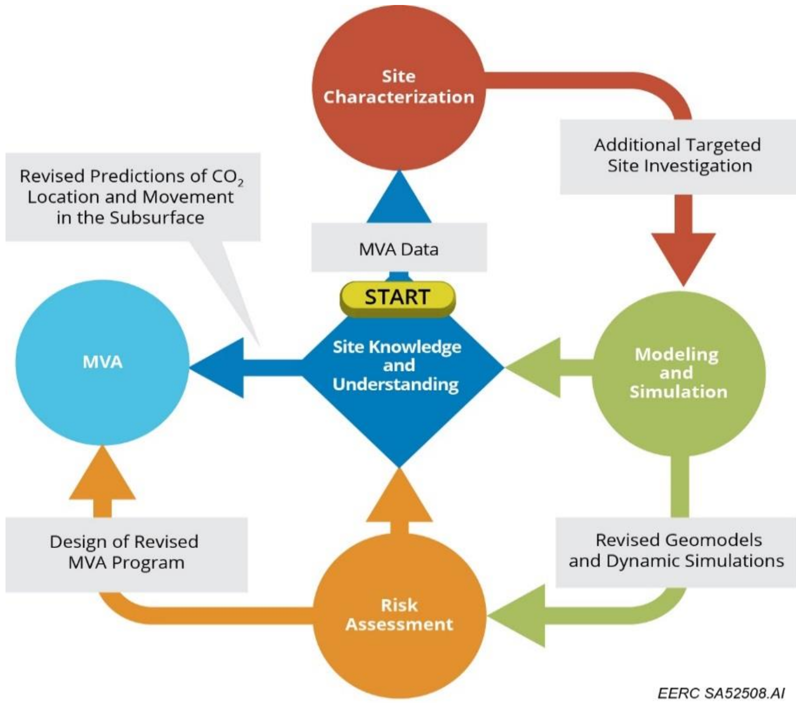

Figure 12. Second iteration of the AMA conducted by the PCOR Partnership during the operation phase of the Bell Creek CO_2 EOR project.

STATE OF BEST PRACTICE – ADAPTIVE MANAGEMENT APPROACH

While the PCOR Partnership has not had an opportunity to apply the AMA during all of the phases of a CO_2 storage project because of the limited duration of the RCSP Initiative, it is anticipated that a project developer could apply the concepts presented in this BPM to successfully execute the AMA during all project phases. PCOR Partnership efforts have demonstrated fit-for-purpose applications of the AMA for both dedicated and associated storage projects as well as the value of the feedback loops, which permit data to move between technical elements to inform and improve their execution over time. This temporal aspect of the AMA is important because of the complexity of commercial CO_2 storage projects and the nature and extent of information that must be gathered during the preoperational development phases. Among the challenges in implementing the AMA is the execution of work such that the feedback loops between technical elements operate in a timely manner during each phase of the project. This can be particularly challenging during the operations phase of a project where MVA technologies, such as time-lapse seismic surveys, may be used to monitor the performance characteristics of a reservoir during CO_2 injection. Since it often takes several months for the collection, processing, and interpretation of these seismic data, it is possible that subsurface operational issues will go undetected during this period, thus delaying the initiation of any preventive or corrective measures. While this challenge can be met through careful project planning, the development of new, innovative monitoring techniques, which provide the same data but in real time, will help facilitate its mitigation.

This BPM presents the basic framework for an AMA for CO_2 storage projects, formalizing it for use at current and future dedicated and associated storage projects. For the purpose of establishing this framework, hard lines have been drawn between the technical elements of the AMA. However, in practice, the rapid and seamless interaction between the elements can blur these lines. Similarly, the exact boundary or scope of a particular life cycle phase may vary from project to project, with the various phases potentially overlapping one another based on the perspective and needs of the individual project operators. Based on the documented applications to date, the AMA approach can successfully integrate the critical technical activities required during the feasibility and operations phases of a CO_2 storage project and is capable of incorporating new information over time. As noted at the beginning of this BPM, the AMA presented here represents a snapshot in time, which will no doubt be modified and adjusted as it is applied and documented at future CO_2 storage projects and extended to other project phases. For example, as certain MVA technologies improve and provide more real-time data, the feedback loops of the AMA may be streamlined to allow more rapid updating of the other technical elements. This continuous improvement of the AMA, and its extension to other project phases, will help ensure that it can be used for the safe and effective commercial development of CO_2 storage projects.

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