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

NEXUS OF WATER AND CCS: FINDINGS OF THE WATER WORKING GROUP (WWG) OF THE REGIONAL CARBON SEQUESTRATION PARTNERSHIPS

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Prepared for:

William W. Aljoe

National Energy Technology Laboratory
U.S. Department of Energy
626 Cochrans Mill Road
PO Box 10940
Pittsburgh, PA 15236-0940

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Prepared by:

Ryan J. Klapperich
David V. Nakles
Edward N. Steadman
Charles D. Gorecki

Energy & Environmental Research Center
University of North Dakota
15 North 23rd Street, Stop 9018
Grand Forks, ND 58202-9018

Andrea T. McNemar

U.S. Department of Energy
National Energy Technology Laboratory

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EXECUTIVE SUMMARY

A Water Working Group (WWG) was formed by the Regional Carbon Sequestration Partnerships (RCSPs) of the U.S. Department of Energy (DOE) in 2009 to identify and address the water-related challenges associated with the commercial deployment of carbon capture and storage (CCS) in the United States. The WWG, which consists of a team of experts from government, academia, and industry, initiated its efforts with the preparation of a white paper on the nexus of CCS and water. This white paper summarized the CCS processes and technologies that affect water usage, described the types of water that exist in deep formations targeted for storage, and described the potential impacts of CO_2 storage on existing formation fluids as well as potable water resources. Also addressed were the treatment technologies that may be applied to water produced (extracted) from these deep formations during CO_2 storage, including opportunities to utilize this water, as is or following treatment. This initial effort was followed by a technology gap assessment workshop, which identified gaps for a number of technical challenges created by the CCS–water nexus, and a stakeholder survey. Broadly speaking, the topics of most concern to the CCS stakeholders were the technical and economic challenges associated with the capture of CO_2 and the potential impacts to water resources, followed closely by the mitigation of potential water impacts. The WWG then proceeded to conduct a mixture of stakeholder and technical outreach activities that were focused on facilitating the transfer of previous research as well as spurring the conduct of future research that targeted these water-related challenges, opportunities, and concerns.

Concurrent with the efforts of the WWG, water-related CCS research was also conducted by various members of the RCSPs, as well as other branches of DOE (e.g., Crosscutting Research Division of the Strategic Center for Coal). This work covered a wide array of topics such as the characterization, treatment, and utilization of extracted formation brines; the impact of CO_2 injection and storage on the characteristics of formation brine; and the investigation and application of techniques for monitoring the presence and movement of contaminants in formation brines.

Much of the efforts of the WWG were focused on describing, summarizing, and communicating DOE research efforts that comprised water-related conceptual and feasibility studies and bench-scale, pilot-scale, and large-scale demonstration projects to stakeholders both within and outside the research community. These research efforts have provided, and continue to provide, valuable information and data for understanding the CCS–water nexus. The future research efforts of DOE and others are moving toward the conduct of larger, near-commercial-scale CCS operations, which will provide much more robust data sets. These data sets can be used to refine both the current technical and economic evaluations of the various formation water management strategies and to support the optimization and final selection of commercial approaches for extracted formation water management.

NEXUS OF WATER AND CCS: FINDINGS OF THE WATER WORKING GROUP (WWG) OF THE REGIONAL CARBON SEQUESTRATION PARTNERSHIPS

INTRODUCTION

The implementation of carbon capture and storage (CCS) to reduce the atmospheric emissions of carbon dioxide (CO_2) from hydrocarbon-based power plants and other point sources will result in an increase in water demand, with additional water requirements driven largely by process changes, increases in makeup and cooling water requirements, the compression and transmission of the captured CO_2 and, at power production facilities, the need to generate replacement power to make up for parasitic load losses. At the same time, there is a potential to generate water during the geologic storage of CO_2 if the withdrawal of water from the storage formation is used as a means to manage subsurface pressure and/or to increase the CO_2 storage potential of the formation. Depending upon the quality of this extracted water and the relative locations of the CO_2 sources and the geologic storage site, it may be possible to use the extracted water to supply the additional water needs created by the CCS operations and, in some instances, to provide excess water for beneficial reuse in the region.[1]

Many challenges must be addressed to meet the increased water demands associated with the commercial deployment of CCS technology. To identify and address these new water challenges, as well as the associated opportunities for water generation and reuse, a Water Working Group (WWG) was formed by the Regional Carbon Sequestration Partnerships (RCSPs) of the U.S. Department of Energy (DOE) in 2009 (Water Working Group, 2010). The WWG consists of a team of experts from government, academia, and industry whose goal is to address stakeholder concerns regarding the commercialization of CCS facilities and their potential interactions with local and regional water resources. The WWG initiated its efforts with the preparation of a white paper on the nexus of carbon capture and storage and water, which was published in January 2010 (Gorecki and others, 2010). This white paper summarizes the processes and technologies of CCS that pertain to water usage, describes the types of water that exist in deep formations targeted for storage, and describes the likely impacts of CO_2 storage on existing formation fluids as well as potable water resources. The treatment technologies that may be applied to water produced from these deep formations during CO_2 storage are also addressed, including opportunities to utilize this water as a resource for beneficial reuse.

[1] The formation water that is extracted at a site will vary in salinity depending upon the location of the site and depth of the storage reservoir. For this reason, the term "water" may include water with low-ppm salt concentrations ranging to as high as several weight percent. As such, references to formation "water" throughout the remainder of this paper are often synonymous with the term formation "brine."

In May 2010, the WWG members conducted a workshop on the challenges and opportunities associated with the CCS–water nexus. The workshop results were published in September 2011, providing a technology gap assessment for a number of water-related challenges (Klapperich and others, 2011). In the same time frame, assessments of the CCS–water nexus were also conducted by other government agencies and the national laboratories of DOE (Birkholzer and Zhou, 2009; Newark and others, 2010; Buscheck and others, 2011). Following the publication of the technology gap assessment, WWG members proceeded to conduct a survey of selected stakeholders to identify the areas of interest or concern that these groups had with respect to water and CCS as a means to better focus future WWG efforts. Based on this information, the WWG proceeded to conduct a mixture of targeted stakeholder outreach and technical activities that addressed these challenges, opportunities, and concerns. It is important to note that the WWG was not funded to perform water-related CCS research. Therefore, most of its efforts supported the framing of the technical, economic, and regulatory issues of the CCS–water nexus and the execution of outreach activities to provide that information. Updates on water-related techno-economic and regulatory developments were also provided to other researchers and a variety of third-party stakeholders. However, concurrent with these efforts of the WWG, water-related CCS research was being performed by each of the RCSPs, as well as other parts of DOE (e.g., Crosscutting Research Division of the Strategic Center for Coal), using existing budgets and/or new technical project awards. These research efforts have provided, and continue to provide, valuable information and data for the management of the CCS–water nexus.

This paper provides an overview of the CCS–water nexus framework developed by the WWG and a time line of the primary stakeholder and technical activities of the WWG for the period from 2009 through 2017. A brief summary of the findings and observations of the WWG related to stakeholder concerns and targeted research performed by the RCSPs is included on the following technical topics: 1) impact of water consumption in the siting of CCS operations, 2) assessment of the cost/benefit of extracting formation water, 3) treatment and beneficial reuse of extracted formation water, 4) regulatory and long-term monitoring considerations, and 5) overarching economic considerations that have the potential to influence water management activities associated with CCS. Finally, a description of complementary water initiatives initiated by DOE to further examine and optimize water management with CCS beyond 2017 is also presented.

CCS–WATER NEXUS FRAMEWORK

A framework for the CCS–water nexus was developed by the WWG (Klapperich and others, 2014a). This framework was based on a water management flow sheet that has evolved over time (Figure 1). As shown in Figure 1, the WWG focused on power generation and oil refining as the sources of CO_2 since they both represent primary targets for CCS. An examination of the CCS–water nexus for other industrial sources of CO_2 emissions such as ethanol, cement, or fertilizer production, to name a few, was beyond the scope of the WWG. However, the same approach and technical assessments conducted by the WWG for power generation/refining are applicable to the deployment of CCS at these other industrial sources.

As depicted in Figure 1, the CCS–water nexus comprises three primary components: 1) CO_2 capture, 2) CO_2 compression and transport, and 3) the geologic storage of CO_2. The primary water impacts associated with each of these components are as follows:

- CO_2 Capture: The implementation of CCS will increase the freshwater withdrawals and consumption of power necessary to accommodate the capture process cooling loads as well as the energy requirements of several major and minor subprocesses associated with the carbon capture technology. The extent of this increase for new plants, as compared to the same plant without carbon capture technology, has been estimated to be 1) 90% for new subcritical and supercritical pulverized coal (pc)-fired power plants using amine-based CO_2 capture systems, 2) 76% for natural gas combined-cycle (NGCC) plants that also deploy the amine-based capture system, and 3) 45% for integrated gasification combined-cycle (IGCC) plants that utilize the Selexol process for the capture of the CO_2 (Klapperich and others, 2014a).

- CO_2 Compression and Transport: The captured CO_2 is typically compressed to, and maintained at, its supercritical pressure (72.8 atm or 1071 psia at T_c of 88°F) during pipeline transport. A pressure of approximately 150 atm (2200 psia) is targeted to transport CO_2 a distance of 80 km (~50 miles) via pipeline without the need for booster recompression stations. In one instance, a pressure of 184 to 202 atm (2700 to 2964 psig) has been used in a pipeline to transport CO_2 over a distance of ~322 km (~200 miles) (Klapperich and others, 2014a). This compression of the captured CO_2 consumes both energy (i.e., additional load for operating the compressors) and water (e.g., water for interstage cooling of the compressors) with estimates of the latter of approximately 0.01 gallons per additional kWh required to transport the captured CO_2 to its destination (Klapperich and others, 2014a).

- Geologic Storage of CO_2: In some instances, water will be generated during the geologic storage of CO_2 as formation water is actively removed from a storage reservoir during a process identified as active reservoir management (ARM). ARM is employed for a number of possible reasons, including increasing the CO_2 storage volume of the reservoir, aiding in the management of CO_2 plume migration, reducing cap rock exposure to CO_2, managing the pressure of the storage reservoir, and/or generating a new source of water for beneficial reuse at the surface. The quantity and quality of the water that is generated during ARM will be driven by many site-specific factors. In most cases, it is expected that the extracted water would be managed by directly injecting it into an appropriate overlying saline formation or formations, although indirect benefits may be derived through the treatment and sale of the extracted water, especially in those areas where water demands are excessive and water resources are limited.

Minimizing the net water consumption of CCS while simultaneously ensuring that the injected CO_2 remains underground and does not migrate into underground sources of drinking water (USDW) represents a key technical requirement during the commercial deployment of CCS.

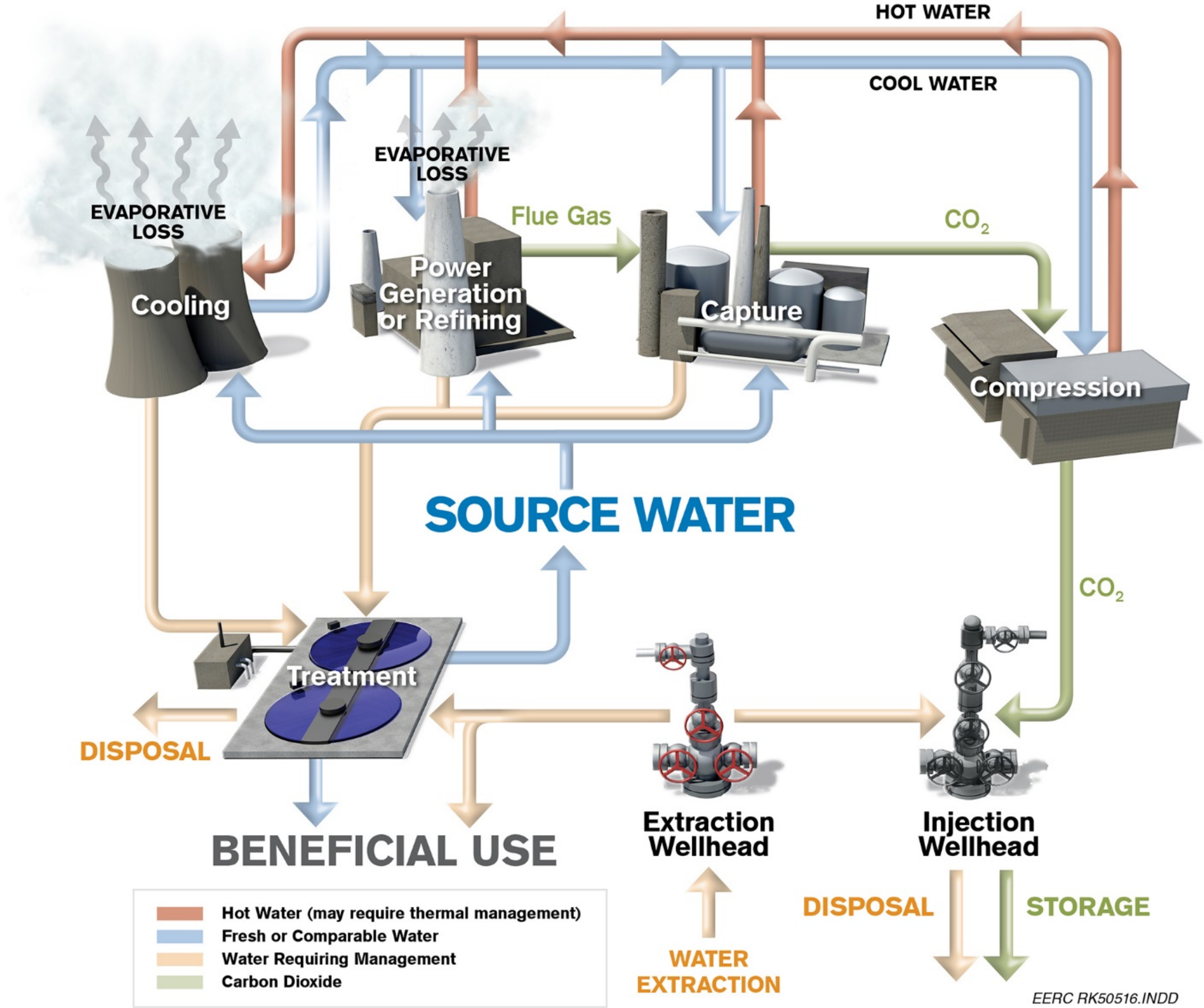

Figure 1. The deployment of CCS will result in an increase in water usage at carbon sources and may also generate water for beneficial use in proximity to the storage sites. Blue arrows represent water withdrawn from surface water or groundwater sources as well as water that may be returned to the original or a related source. Red arrows represent hot water sent to cooling facilities. Green arrows represent the flow of CO_2 through the system. Tan arrows represent water requiring some form of management prior to its final disposition.

OVERVIEW OF THE WATER WORKING GROUP ACTIVITIES

The activities of the WWG were focused on achieving two primary objectives: 1) addressing stakeholder concerns regarding the potential interactions of commercial CCS operations with local and regional water resources and 2) defining the technical challenges and opportunities associated with managing the CCS–water nexus and facilitating the technical transfer of research that was performed by the RCSPs to overcome the challenges and exploit the opportunities. An overview of the specific stakeholder outreach and technical activities that were performed by the WWG since its inception in 2009 through the end of its tenure at the conclusion of calendar year 2017 are provided below:

- Multiple technology-transfer tools, which included fact sheets, a WWG Web site, and a standardized WWG presentation, were developed to facilitate communication of the WWG findings and observations to a variety of CCS stakeholders.

- Monthly conference calls and six annual meetings, which included invited speakers, were used to facilitate the timely exchange and discussion of information among the WWG representatives of the RCSPs and other stakeholders regarding the CCS–water nexus.

- Milestone and/or value-added technical reports and publications were issued that framed the CCS–water nexus, defined the technical challenges and opportunities created by this nexus that are facing commercial CCS developers, and identified the technology gaps that remain to be addressed for this greenhouse gas reduction strategy.

- A targeted set of published manuscripts were generated and/or compiled that focused on the CCS–water nexus.

The reference section of this paper provides an abbreviated CCS–water nexus bibliography which comprises the relevant reports and manuscripts that were generated by the members of the WWG over the period from 2009 through 2017, as well as selected other key sources of technical information.

More details regarding the specific findings and observations of the WWG are provided in the remainder of this paper.

STAKEHOLDER CONCERNS AND OUTREACH

Potential CCS–Water Stakeholder Concerns

In late 2011, the WWG had convened a technology gap assessment workshop, which identified the technical challenges and opportunities associated with the CCS–water nexus (Klapperich and others, 2011). As part of that assessment, the members of the WWG also identified and discussed a number of potential stakeholder concerns covering a wide variety of topics. These included the potential for inducing water scarcity and increasing water utility rates, the siting of the required infrastructure including operating/storage facilities and pipelines, water handling and safety procedures, accidents, and environmental and health effects.

Among the stakeholders of interest to the WWG were government agencies, power suppliers and other industry groups, water suppliers, agricultural organizations, environmental groups, and water users. To better understand the concerns of this mix of stakeholders, the WWG conducted a nonscientific survey in 2012 that involved 15 third-party CCS stakeholders. The survey posed a series of questions to the survey participants that attempted to 1) determine their general attitudes toward CCS and the impact of CCS commercialization on energy security and the environment,

2) determine their level of interest in a variety of water-related technical/regulatory topics, 3) develop an initial list of major challenges that represent potential barriers to the widespread deployment of CCS, and 4) identify perceptions regarding the current technical understanding of the potential water impacts of CCS and the availability of monitoring and/or mitigation strategies for their management.

The results of this initial survey revealed the following:

- While only a limited number of survey respondents believed that CCS would benefit energy security (27%) or the environment (45%), 91% of survey respondents agreed or strongly agreed that CCS could potentially impact the supply and quality of water resources.

- Potential impacts to water resources and the technical challenges associated with the capture of CO_2 were the topics of most interest to the survey respondents (90% of survey respondents were very interested or somewhat interested), followed closely by water impact mitigation (83% of survey respondents were very interested or somewhat interested). All other topics, e.g., technical challenges associated with the geologic storage of CO_2, water extraction, liability, regulatory frameworks, and pore space ownership were of less interest to the respondents (i.e., 73% or less).

- Survey respondents believed that concerns over the increased water use of CO_2 capture systems (60% of survey respondents) and potential water quality impacts of the geologic storage of CO_2 (50% of survey respondents) represented potential barriers to the commercial deployment of CCS. At the same time, 20% or fewer of the respondents believed that the potential impacts of CCS on the quality of water resources were well understood or that adequate strategies existed to monitor or mitigate these impacts.

Many of the above stakeholder concerns reflect the lack of a conceptual understanding of the hydrogeological concepts that govern CO_2 storage in, and formation water extraction from, a "saline aquifer" as well as the potential benefits of the geologic storage of CO_2 and the motivating factors driving the commercial deployment of the CCS industry. For this reason, it was imperative that an active stakeholder outreach program be implemented by the RCSPs and others to better inform stakeholders of the basic science that underlies CCS and how both the government and private sector are focused on the management of CCS to address potential health and environmental risks associated with its commercial deployment.

Stakeholder Outreach Activities of the WWG

The 2012 stakeholder survey also requested input to guide the development of an outreach program for the WWG. The results of the survey revealed that fact sheets (91%) were the preferred means of receiving information about CCS, in general, and the CCS–water nexus, in particular, followed by presentations, newsletters, and a dedicated Web site (64% of the respondents supported each of these approaches). The use of Webinars or interactive workshops/seminars were identified as the least desirable means of receiving information (i.e., <36%).

The WWG used these survey results to guide the deployment of several methods to disseminate information regarding the CCS–water nexus to the WWG stakeholders. Details regarding these actions of the WWG are provided below:

- Four fact sheets were created, one of which introduced the WWG and its mission ("Regional Carbon Sequestration Partnership Water Working Group" [Water Working Group, 2010]) and three of which focused on one particular stakeholder concern, the protection of water resources ("Carbon Capture Utilization and Storage [CCUS] and Water Resource Protection" [Water Working Group, 2013a]; "Monitoring, Verification, and Accounting Plans for Protection of Water Resources During the Geologic Storage of Carbon Dioxide" [Water Working Group, 2013b]; and "Long-Term Protection of Freshwater Resources Following CO_2 Storage" [Water Working Group, 2014]).

- A dedicated WWG Web site was developed and is hosted on the National Energy Technology Laboratory's (NETL's) Web site as part of the Carbon Dioxide Storage Program description (www.netl.doe.gov/research/coal/carbon-storage/wwg).

- A standardized PowerPoint presentation, "Regional Carbon Sequestration Partnership – Water Working Group," was created by the WWG in July 2011 to describe the WWG and its primary goals and objectives. This presentation was disseminated to the RCSPs, where it was used at several CCS conferences and symposiums. In addition, since that time, each of the RCSPs has made both poster and platform presentations at numerous seminars, workshops, and/or conferences that provided updates of the activities and progress of the WWG. These presentations were open to the public and were often published in publically available conference/meeting proceedings.

These water-focused stakeholder interactions represented a major initiative of the WWG and were shared with the Public Outreach and Education Working Group, which was also formed in a similar time frame by DOE.

TECHNICAL GAPS ASSESSMENT

The technical focus of the WWG was also guided by the technology gap assessment workshop. The technical topics of interest that were identified during the workshop included 1) impact of water consumption on siting of CCS operations, 2) assessment of the cost/benefit of extracting formation brine, 3) treatment and beneficial reuse of extracted brine, 4) water-monitoring considerations, and 5) potential cost externalities associated with water management during the deployment of CCS operations. A list of the challenges and opportunities that were identified for each of these topics during the workshop are documented in Klapperich and others (2011) and are briefly summarized herein along with the subsequent findings and observations of the WWG in each of these technical areas.

Each of the following subsections contains a description of the technical challenges and opportunities for various facets of the water–CCS nexus as well as observations and findings of the WWG while researching each facet.

Impact of Water Consumption on Siting of CCS Operations

Water supply challenges facing the energy industry have the potential to be exacerbated by the commercial deployment of CCS. As noted earlier in this paper, significantly increased water consumption can be expected with the addition of carbon capture processes, the compression and transport of the captured CO_2, and the final subsurface disposition of the CO_2. At the same time, additional water, in the form of extracted formation water, may be generated during storage of CO_2 if ARM is practiced. Should a net increase in water demand occur, it will be particularly problematic in those areas of the United States where a scarcity of water already exists and may be sufficient to preclude the siting of the CCS operations. However, in those instances where the water balance yields a net production of water, CCS operations may provide an additional water resource for use in these same water-stressed regions.

One of the first initiatives of the WWG was to establish a framework for the CCS–water nexus and to examine the water requirements for implementing all phases of CCS, including CO_2 capture, compression and transport, and geologic storage (Klapperich and others, 2014a). These efforts documented that while water consumption will increase during the commercial deployment of carbon capture systems and the pipeline transport of the captured CO_2 to the geologic storage sites, the potential also exists to generate water from the target storage formations as part of an ARM program. The extraction and potential use of the storage formation water has been compared to the practices deployed in the oil and gas industry for produced water management (Veil and others, 2011). The approach to manage the CCS water balance will depend upon several site-specific factors such as the characteristics of the anthropogenic source of the CO_2, the carbon capture technology used, the volume of CO_2 captured and the distance it must be transported, and the quality of the water in the target storage formation, to name a few.

The ability to implement CCS such that there is no net increase in water consumption or even a net production of water is critical for its deployment in regions where water is in short supply. For example, a study of regional water stress in Europe revealed that, in 2050, water stress could substantially increase if there is a high penetration level of carbon capture technologies in European power plants (Schakel and others, 2015). A somewhat similar study was conducted in the United States that examined the effect of CCS implementation on water-stressed regions by conducting a geospatial analysis that detailed the county-level balances of water supply and demand across the contiguous United States. This study concluded that CCS can strongly affect freshwater supply and demand in specific regions, with the importance of extracted formation water increasing as freshwater supply becomes more limited (Sathre and others, 2012).

From a water balance perspective, other studies have demonstrated that the extraction of formation water from the storage reservoir could provide enough water to meet one of the major CCS water demands (i.e., all CCS-related cooling demands) of a representative NGCC power plant for 177 of 185 saline formations in the United States (Klise and others, 2013). Another study, following an examination of three locations in the United States, concluded that regionally appropriate management strategies could be developed to treat extracted formation water as a source of revenue, energy, and water (Breunig and others, 2013).

Assessment of the Cost/Benefit of Extracting Formation Brine

As part of an ARM strategy, formation water is extracted to increase the storage volume of CO_2 in a target formation as well as reduce local or regional formation pressure during CO_2 injection. This action may also be used to control the migration of CO_2 within a specific formation or basin. The extracted formation water will likely be saline and contain a variety of different constituents, depending upon the regional geology and the subsurface depth. The quality of any extracted water will be a primary factor when the economic viability of employing formation water extraction as an approach for managing a CO_2 storage site is determined. In some circumstances, targeted storage formations may contain water with concentrations of total dissolved solids (TDS) exceeding those of protected water status (>10,000 mg/L TDS) but yet still be sufficiently low to allow economical treatment for other recycle/reuse strategies and/or surface disposal.

The off-site recycle or sale of these waters for beneficial use may further offset the local or regional increase in water demands as well as to the added cost of carbon storage. However, if the formation water contains relatively large concentrations of unwanted constituents, the costs of water treatment and processing may outweigh the potential benefit of increased CO_2 storage potential and/or the revenue generated by the sale of the processed water to potential end users. In these cases, the extracted water will likely have to be reinjected into the same formation or another suitable formation, or it may be decided to forego increasing the storage potential of the site by not extracting any formation water from the subsurface. At the same time, water rights and pore space ownership must be determined as a basis for 1) assessing royalty charges for their use, 2) conducting a realistic valuation of saline formation water, 3) avoiding legal challenges and litigation, and 4) properly regulating formation water extraction and discharge. The latter may be complicated by issues such as 1) cross-boundary relationships (political or watershed); 2) varying and conflicting local, state, and federal legal frameworks; and 3) water-handling/safety procedures. In the end, the extraction of formation water from a CO_2 storage site will be a site-specific decision based on a combination of site-specific technical factors and economic trade-offs.

Generally speaking, ARM through formation water extraction has the potential to maximize the utility of deep saline formations as a resource for CO_2 storage. A detailed analysis of this potential was funded by the IEAGHG (International Energy Agency Greenhouse Gas R&D Programme) to investigate the ability to manage formation pressures, increase reservoir storage capacity, control CO_2 plumes, and control the migration of displaced formation water (IEA Greenhouse Gas, 2012; Klapperich and others, 2013, 2014b; Liu and others, 2013, 2015). Four case study sites were analyzed as part of this effort: the Ketzin Site in Germany, the Zama Field in Canada, the Gorgon project area in Australia, and the Teapot Dome Field in the United States. These sites represent a range of geologic flow lithologies, sealing formation geometries, hydrogeologic regimes (open, semiclosed, or closed systems), and storage formation salinity. Several conclusions resulted from this study:

1. Reservoir-scale dynamic simulations indicated that potential increases in CO_2 storage capacity varied greatly based on site conditions (i.e., increases in the CO_2 storage capacity of 4% to 1300% were projected across the four case study sites) with higher water extraction rates generally providing better formation pressure and plume management. This resulted in higher ratios of water extracted to CO_2 storaged (as high as 4:1) where

plume and pressure management were primary drivers as opposed to maximizing increases in storage capacity. Other observations were as follows:

- Extracting water from a CO_2 storage reservoir was observed to have variable effects based on the specific nature of reservoir rock and reservoir boundary conditions as well as operational factors such as injection/extraction management and well placement.

- Formation water extraction was found to be effective to control pressure and increase storage space in closed systems where the injected volume accounts for a relatively large portion of the available storage volume in the reservoir. Extraction would likely provide benefit to many semiclosed, bounded reservoirs if water disposal or beneficial use is not prohibitive.

- The influence of formation water extraction on the migration of pressure and free-phase CO_2 plumes was observed in each of the open-system sites. However, this influence was moderated by other factors such as geologic structure and local reservoir heterogeneities.

- The utilization of formation water extraction for the purpose of reservoir management is best applied to reservoirs with low structural relief. In dome-shaped structures, formation water extraction did not appear to have a strong effect on the structure-dominated CO_2 movement. However, in the case of a relatively flat-structured reservoir, CO_2 plume and pressure management results were significantly affected by formation water extraction.

2. Investigations of the surface dissolution of CO_2, where CO_2 is blended with extracted water at the surface prior to injection into the storage reservoir, was investigated at two of the sites. This investigation at the Ketzin and Teapot Dome sites revealed that the removal and reinjection of very large volumes of water only provided a small fraction of additional CO_2 storage capacity when injecting supercritical CO_2. Furthermore, it was determined that the required temperature and pressure conditions to maintain CO_2 in solution and to control corrosion and scaling presented both technical and economic challenges that reduced the applicability of this approach as an alternative to the injection of pure-phase CO_2.

3. Treatment costs were estimated for several commercial technologies to provide beneficial use of extracted waters over the range of water quality identified for the case study sites. The costs of desalination were found to be too high to make treatment a viable option over disposal via deep well injection. Furthermore, coastal or off-shore sites would likely use seawater desalination to provide a beneficial use resource over extracted water, especially if transportation costs are considered.

4. There were no identified regulatory barriers in any of the jurisdictions reviewed regarding the extraction of formation water as a pressure management technique for CCS projects. Regulatory authorities and industry have developed regulatory processes and best

practices that provide for the safe and cost-effective subsurface disposal of wastewater for other industries which should be transferable to the extracted formation water of CCS operations.

Other site-specific technical considerations that are important to implementing this approach to ARM are changes in the formation water characteristics that can occur over time during its extraction and/or reinjection (Berger and others, 2016). For example, geochemical modeling has indicated that mineral precipitation can occur as extracted formation water is exposed to oxygen and cools, and reinjected formation water can react with the minerals in the subsurface formations, leading to changes in the mineralogy and brine composition.

In summary, the ability to beneficially use the extracted water will depend upon the quality and quantity of the water and its proximity to an end user of the resource. Most of the beneficial use options for extracted water will require the removal of TDS, with economical treatment limited to formation water quality typically not exceeding TDS levels of sea water where higher-quality end use is desired. However, the treatment of high-TDS extracted water for beneficial use, while technically feasible, is likely to be economically prohibitive. Ideal circumstances for considering the deployment of formation water extraction combined with treatment and beneficial use of the extracted water consist of the coexistence of relatively high quality formation water in a region with highly stressed or limited water resources. This approach was confirmed by a system-level analysis that was performed to assess the benefits of extracting and treating saline water from geologic formations during the deployment of CCS on a national scale (Roach and others, 2016). This study concluded that the majority of storage associated with large-scale CCS in the United States would occur at a small number of well-located sites with favorable geologic properties. Using marginal abatement cost curves, this study showed that under such a scenario, the added costs associated with resident saline water extraction, transport, and treatment would be justified by the resulting increases in CO_2 storage efficiency in the geologic formation.

Treatment and Beneficial Reuse of Extracted Formation Water

The treatment of extracted water during CCS presents a variety of unique challenges and opportunities related to the characterization of the formation water, the potential lack of cost-effective treatment technologies and commercial-scale applications, and the numerous market opportunities for beneficial reuse of the extracted water. More specifically:

- The quality of the extracted formation water can vary significantly between sites and over time, making it difficult to predict the chemical characteristics of the formation water during extraction and to select/compare site-specific treatment strategies for both associated and dedicated CO_2 storage projects.

- There is a potential lack of cost-effective treatment technologies to address 1) removal of trace contaminants, 2) control of scale and corrosion, and 3) management of liquid concentrates and/or dry residuals produced during treatment of the extracted formation water.

- Development of commercial-scale treatment strategies are complicated by several factors such as 1) the inability to scale up processes based on laboratory- or pilot-scale treatability studies, 2) the potential for complex or costly problems to result from the application of complex treatment schemes, 3) the difficulty in predicting extraction volumes and rates as well as appropriate injection volumes and rates, 4) the need for improvements in pretreatment options for the removal of organics, boron, silica, etc., and 5) the potential presence of naturally occurring radioactive material (NORM).

- Numerous market opportunities for the beneficial reuse of extracted water should be explored, including 1) oil/gas industry use (water flood, pressure control, hydraulic fracturing, etc.), 2) power industry use (cooling water, process water, etc.), 3) general industry use (process water, wash water, etc.), 4) extraction of ions (lithium, carbonates, etc.) and rare-earth elements for sale, 5) source of thermal energy, 6) sources of water for algal growth (biofuels, pharmaceuticals, etc.), 7) agricultural use (e.g., irrigation), 8) subsidence control, 9) mining of dissolved salts and minerals (e.g., road salt production, brine for use in mineralization-based carbon capture processes), 10) residual methane production, 11) artificial recharge, and 12) saltwater intrusion barriers.

It is evident that the treatment of extracted formation water remains largely undeveloped and could potentially limit the application of water extraction as a strategy for increasing carbon storage capacity and/or generating water as a potential resource. If these typically saline waters also contain other minor constituents (e.g., trace hydrocarbons, NORM, etc.), additional problems may be encountered for both their handling and treatment. Information gathered by the WWG on the quality of extracted formation water, potential direct and beneficial use options for this potential resource, and the treatment technologies available for implementing these water management strategies will be helpful in further framing this issue for stakeholders interested in the beneficial reuse of extracted formation water.

The quality of extracted formation water will vary from low-salinity water, typical of former oil and gas reservoirs where hydrocarbons may be the main component of concern, to very high salinity waters where beneficial use of the water is unlikely but options for recovery of the geothermal heat, salts, and/or minerals may be possible (Klapperich and others, 2013). For example, the average TDS concentration in the formation water of Mt. Simon Sandstone, a target storage formation in the Illinois Basin, was reported as 190,000 mg/L, with the primary constituents identified as chloride (120,000 mg/L), sodium (50,000 mg/L), and calcium (19,000 mg/L) (Locke and others, 2013). The composition of other formation waters from this Cambrian-age stratum illustrate the degree of variability that can exist in these formation waters as a result of the variety of mechanisms that are responsible for their formation, e.g., the chloride concentrations from multiple formations ranged from 5000 to >179,000 mg/L (Panno and others, 2013). This variability in the composition of formation waters has also been documented at a nationwide scale, where TDS concentrations were shown to range from 1,000 to 400,000 mg/L (Wolery, 2012).

The WWG identified numerous direct use/beneficial use options for extracted formation water (Klapperich and others, 2014a): 1) power plant cooling water; 2) gray water for industrial (e.g., pulp and paper production, cement production, textile and tanning industry) and municipal (e.g., hospitals, restaurants, schools) uses; 3) drinking water for livestock and agricultural irrigation; and 4) a water source for surface flow augmentation, the control of saline water intrusion into drinking water aquifers, and the generation of potable water. The WWG also reviewed the treatment required to take advantage of these end-use options and concluded that conventional physical, chemical, and thermal treatment technologies currently exist to permit the implementation of many, if not most, of these water management strategies, although in many cases, it is expected that the cost of this treatment will be significant. There are feasibility and economic analysis tools available to fully examine the costs and benefits of treating extracted formation water for beneficial use (Klise and others, 2013; Sullivan and others, 2013; Kobos and others, 2011, 2016; Roach, 2016; Advanced Resources International, 2014). The analyses that have been performed to date are limited by the lack of economic data for commercial-scale water treatment facilities.

Water-Monitoring Considerations

Subsurface monitoring will be an important component of all CCS applications. The two primary goals of this monitoring effort are to confirm the containment of the injected CO_2 in the storage reservoir and the protection of any nearby USDWs. The nature and extent of these monitoring efforts will be dictated by a combination of the applicable local, state, and federal regulations, site-specific risk assessments, and critical stakeholder concerns. It is possible that conflicts may arise related to water law or between stakeholders and regulators during the merging of these requirements. Particularly significant are evolving regulatory requirements that require the monitoring, verification, and accounting (MVA) of the injected CO_2 for both environmental as well as business accounting purposes, e.g., the ability to qualify for tax incentives based on the amount of CO_2 stored (Federal Register, 2010).

Significant challenges and opportunities are associated with the water-monitoring considerations at the CCS–water nexus. Goals of a water-monitoring program for CCS operations would be to accurately assess and account for the water-related risks of the operation by:

1. Evaluating the potential for impacts from the long-term storage of CO_2, which may include impacts to the physical, chemical, and geochemical characteristics of reservoir rock and cap rock as well as formation water chemistry and composition.

2. Identifying potential for significant reservoir leakage and mobilization impacts by a) identifying key leakage indicators for CO_2 and brine; b) recording evolution of pressure fronts and potential for overpressurization in the reservoir; c) modeling potential for brine displacement and migration; d) evaluating dissolution and mobilization of organics and metals; and e) identifying potential impacts on resources, including potable groundwater and mineral resources.

3. Demonstrating that a storage reservoir is effectively containing injected CO_2 and that carbon storage activities are being protective of water resources through a) detection of plume movement, b) characterization of baseline reservoir and lowermost USDW conditions, c) measuring geochemical constituents that may indicate impact from carbon

storage activities, d) validation of modeling efforts with field data, and e) supporting material balance calculations to account for the total CO_2 injected.

In addition, regulatory uncertainty continues to exist because of 1) conflicting regulatory objectives (e.g., oil and gas regulations versus clean water regulations); 2) an inability to reconcile political versus hydrogeological boundaries; 3) regulatory divisions between federal, state, and local authorities; and 4) potential increases of the maximum TDS limit (10,000 ppm) for reinjection, which has been advocated by some nongovernmental organizations (NGOs).

The WWG stakeholder survey identified the potential impacts of CCS to water resources as a potential barrier to the commercial deployment of CCS. In addition, survey respondents generally believed that the potential impacts of CCS on the quality of water resources were not well understood and that adequate strategies did not exist to monitor or mitigate such impacts. Given these results, the WWG proactively addressed the protection of freshwater resources by addressing it in three of the four fact sheets that were produced by the WWG for stakeholder outreach (Water Working Group, 2013a, 2013b, and 2014), focusing one of them specifically on MVA plans (Water Working Group, 2013b). The MVA fact sheet 1) defined an MVA monitoring framework that focused on three distinct vertical zones: atmospheric, near-surface, and subsurface; 2) presented the monitoring objectives as well as a subset of candidate monitoring technologies for each zone; 3) identified the water resources that are being targeted for analysis as part of the large-scale demonstration projects of the RCSPs and others (e.g., Weyburn–Midale enhanced oil recovery/geologic storage project) and described the general nature of these analyses; and 4) described the MVA plan requirements embodied in the Class VI Rule of the U.S. Environmental Protection Agency (Federal Register, 2010).

Concurrent with these outreach efforts, targeted research efforts that can be used to inform potential monitoring strategies were carried out. These research projects consisted of bench-scale experiments, geochemical modeling, and field sampling/analysis of groundwater and formation water, as described below:

- The bench-scale experiments focused on the examination of potential chemical changes induced by the introduction of CO_2 into the subsurface. These studies revealed that CO_2 can result in a significant decrease in pH, causing both calcite precipitation and dolomite dissolution as well as changes in the chemistry on iron oxide surfaces (Berger and Roy, 2011). The latter was attributed to changes in surface complexation sites of the iron oxide in sandstone formations and resulted in detectable changes of several aqueous iron species. Other bench-scale experiments determined that deep formation water contained low-diversity microbial communities and could be used to establish iron-reducing enrichment cultures, suggesting new mechanisms for microbial iron reduction in the subsurface (Dong and others, 2013, 2014, and 2016).

- Geochemical models were created to simulate changes in the reservoir chemistry and properties in response to the injection of CO_2 during CO_2-enhanced oil recovery (Berger and others, 2009). These models were then used to predict future changes in the reservoir during CCS operations. Other modeling efforts predicted that the potential leakage rates of CO_2 at a storage site would result in the release of additional trace metals into a USDW but would not result in exceedances of regulation-stipulated maximum contamination levels or no-impact thresholds (Xiao and others, 2016). Similar modeling studies on a different aquifer associated with a natural CO_2 analog field site in New Mexico were performed and, combined with field observations and batch laboratory experiments, indicated a deep brackish water was the source of arsenic in the subsurface. This work also suggested that the mobilization of this arsenic would be mitigated by adsorption to clay minerals. In general, it was noted that high salinity hinders the release of arsenic from subsurface minerals (Xiao and others, 2017a, 2017b).

- The sampling and analysis of formation water and groundwater were performed and provided valuable field data to complement the bench-scale experiments; further inform and calibrate geochemical models (Berger and others, 2009; Couëslan and others, 2014); provide information regarding the long-term hydrology of formation water and the hydrodynamics and residence times of isolated aquifers (Giunta and others, 2013, 2017); and provide data for assessing permitting and regulatory compliance (Iranmanesh and others, 2014; Locke, 2013; Locke and Greenberg, 2015; Locke and others, 2017). These field tests were also used to evaluate and compare methods for detecting CO_2 in shallow groundwater (Edenborn and others, 2016).

- Rare-earth elements were evaluated as natural tracers in high-TDS reservoir brines to characterize potential CO_2 leaks at a CCS site, and radon was investigated for the mapping of open fracture networks in thin vadose zones (McLing and others, 2014, 2017a, 2017b).

To date, based on all of the water monitoring that has occurred at CCS sites across the United States, no direct impacts to USDWs have been measured. At the same time, an extensive amount of research is being conducted within the RCSPs and elsewhere to define an optimal set of monitoring technologies, which both meet the necessary technical and regulatory/risk requirements of a monitoring program and are cost-effective. In the meantime, DOE is developing a best practices manual (BPM) to address monitoring at CCS sites; the latest edition of this BPM was published in 2017 (National Energy Technology Laboratory, 2017).

Potential Cost Externalities

The high costs associated with the CCS–water nexus may limit the development and implementation of many water management strategies. However, as previously discussed, it may be possible to reduce the cost of these strategies by implementing ARM, which has the potential to generate a positive revenue stream from the beneficial reuse of the extracted formation water and to reduce the cost of the subsurface water-monitoring requirements through the reduction in the size of the permitted area of review. Additional cost savings may also be achievable by increasing the use of water recycling in CCS operations and by implementing technological improvements that are focused on more effective cooling, compression, and treatment strategies. However, in addition to these cost/benefit considerations, several cost externalities need to be captured to permit a proper economic assessment of the CCS–water nexus. For example, the true cost/value of water resources, which vary by region, basin, regulatory boundaries, and industry types, must be carefully estimated to properly evaluate the potential economic benefit of implementing water management strategies that both conserve water resources and maintain their overall quality. As long as social and political pressures keep the true cost of water resources artificially low and do not reflect the ever-increasing environmental and anthropogenic stresses on many of the existing water systems, the additional costs associated with the CCS–water nexus will likely continue to discourage ARM during the application of CCS. A key tool for addressing these externalities are water life cycle assessments that can be used to evaluate and prioritize future opportunities for reducing the cost of water treatment while still achieving a net positive environmental impact.

The current stage of development of the CCS industry has limited the ability to conduct detailed economic analyses of the CCS–water nexus. The fact that there are currently few large-scale CCS operations in the United States, none of which has been operating for extended periods of time, has resulted in a paucity of commercial-scale operating data available to inform an accurate economic assessment of the cost of water management and its impact on the overall economics of CCS. In addition, few, if any, water life cycle assessments have been performed for a commercial CCS operation. For this reason, the majority of studies to date, which have been performed by NETL and the national laboratories of DOE, have focused on the development of systems and/or water treatment economic models that have been derived from data in the open literature and the results from bench-scale and short-term field-scale studies performed as part of the RCSPs and other CCS-related research programs.

These current modeling studies have been helpful in evaluating the feasibility of developing water management strategies to treat extracted formation water as a source of revenue, energy and water (Breunig and others, 2013; Klise and others, 2013), assessing the benefits of extracting and treating saline water from geologic formations during the deployment of carbon capture and storage on a national scale (Kobos and others, 2011; Kobos and others, 2016; Roach and others, 2016), and evaluating treatment costs for the chemical and physical qualities of formation water that could be extracted from storage reservoirs (Sullivan and others, 2013, 2014; Harto and Veil, 2011; Advanced Resources International, Inc., 2014). Moving forward, as more research and operating data are collected to inform these models, improved economic analyses to examine the life cycle costs and benefits of treating extracted formation water for beneficial use will be possible.

COMPLEMENTARY WATER INITIATIVES

Several other relevant CCS-related water research and/or field programs beyond the efforts of the RCSPs were identified by the WWG. Provided below is a brief summary of the other DOE programs that are significant to the continued examination of the CCS–water nexus.

Framework for Developing a Water for Energy Decision Support Tool (WEDST) for the Coal Sector

The Crosscutting Research Division of the Strategic Center for Coal is conducting research to develop a framework for a Water for Energy Decision Support Tool (WEDST) with a focus on the coal sector. This framework will provide an analytic platform that can be applied to inform technology and supply choices related to water for energy planning at both the regional and national levels and their design and siting decisions. The framework will also offer guidance for close coordination of energy planning and water resource management. A report describing the final framework is expected in FY2018.

WEDST's development is supported by over a decade of water research, which has focused on the identification of projects that will develop a range of technologies to optimize and/or reduce freshwater use for energy processes through improved waste heat recovery, alternative heat transfer technologies, and new sources of water (i.e., utilizing treated wastewater). The most recent project portfolio report showcases 20 water management research and development projects which are focused on the following three topical areas: 1) process efficiency and heat utilization (four projects), 2) water treatment and reuse (14 projects), and 3) data modeling and analysis (two projects) (U.S. Department of Energy, 2017). For the most recent update of the water-related research of this group, the reader is directed to the following Web site: www.netl.doe.gov/research/coal/crosscutting/publications.

Brine Extraction Storage Test Projects

Beginning in 2015, DOE awarded five Brine Extraction Storage Test (BEST) projects. The purpose of BEST field projects is to develop and validate engineering strategies and approaches for managing formation pressure, as well as plume movement in the subsurface, through formation water extraction. The field projects will also help to find cost-effective ways for treating extracted waters to generate a usable water supply and support DOE's objectives to improve water management and conservation for power generation, hydrocarbon production, and industrial processes, particularly in regions where water resources are scarce. These initial projects were awarded to complete the feasibility and design phase of a field demonstration project.

More recently, in 2017, two of these original BEST projects were identified for continued funding to conduct a field pilot project to validate brine/water injection and extraction/treatment strategies. A brief description of these two awards is provided below:

- Electric Power Research Institute – This project will use existing wastewater disposal wells and new wells at Plant Smith (operated by Gulf Power Company) near Panama City, Florida, to demonstrate an adaptive management strategy of subsurface pressure, fluid movement, and differential pressure plume behavior. As part of the pressure management plan developed for the site, wastewater injection and formation water extraction will be conducted into/from the target storage reservoir. The adaptive management strategy designed for this project combines "active" formation water extraction from one well with "passive" pressure relief using another well. In addition, construction of a user-enhanced water recovery (EWR) facility for treating formation water extracted from the storage reservoir is planned. Following treatment, the clean water could be reused for beneficial purposes, including supplemental cooling water at a power station. The water treatment facility will include the testing and validation of novel water desalination technologies.

- The Energy & Environmental Research Center (University of North Dakota) will evaluate ARM approaches for managing formation pressure, predicting and monitoring differential pressure plume movement, and validating pressure and brine plume model predictions at an operating commercial saltwater disposal facility located near Watford City, North Dakota. Engineered formation water brine injection and extraction tests, monitoring and verification programs, and iterative simulation modeling will be used to evaluate and understand the effect of various ARM strategies. A test bed EWR facility will also be operated for the evaluation of selected formation water treatment technologies.

These demonstration tests will provide first-of-a-kind, field-scale data sets that can be used as a basis for assessing both the performance and economics of formation water extraction and treatment at a commercial scale. As noted previously, the lack of field-scale data to date has been a limiting factor in performing reliable economic assessments of formation water extraction and management strategies for commercial CCS operations.

CarbonSAFE

In 2017, DOE also awarded projects as part of the Carbon Storage Assurance and Facility Enterprise (CarbonSAFE) initiative. This initiative is in place to move from the current pilot or short-term, large-scale CO_2 injection tests previously supported by DOE to projects that are intended to develop, through a series of sequential phases, integrated CCS storage complexes. Both Phase I and Phase II projects have been awarded with the objectives of the latter focusing on one or more specific reservoirs within a defined storage complex and comprising efforts in data collection; geologic analysis; identification of contractual and regulatory requirements and development of plans to satisfy them; subsurface modeling to support geologic characterization, risk assessment, and monitoring; and public outreach. Similar to the BEST projects, the CarbonSAFE projects will provide field-scale data that can be used for developing more accurate, improved assessments of the economics associated with CO_2 storage strategies and site characterization.

SUMMARY

The WWG of the DOE RSCPs has been in place since 2009 with the goal of addressing stakeholder concerns regarding the commercialization of CCS facilities and their potential interactions with local and regional water resources. Because of the stage of CCS technology development during the tenure of the WWG, most of the effort was limited to describing and summarizing DOE research efforts that comprised water-related conceptual and feasibility studies and bench-scale, pilot-scale, and short-term duration, large-scale demonstration projects. During this period, ARM evolved as a potential means for improving the safety and performance of the geologic storage of CO_2. However, the technical and economic feasibility of managing the extracted formation water for final disposition remains uncertain, largely because CCS operations have not yet been conducted at a scale or duration sufficient to adequately investigate this challenge. At the same time, models to perform initial CCS systems analysis and formation water treatment evaluations have been developed and used to confirm the potential viability of deploying a formation water extraction and management strategy that comprises disposal and/or beneficial reuse options capable of providing a revenue stream to defray the cost of treatment. These models have been supported by a number of research studies performed by the RCSPs and others, some of which have been completed and others that are still in progress. The future research efforts of DOE and others are moving toward the conduct of larger, near-commercial-scale CCS operations, which will provide much more robust data sets. These data sets can be used to refine both the current technical and economic evaluations of the various formation water management strategies and to support the optimization and final selection of commercial approaches for extracted formation water management.

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